PB84-210293

Corrosion Manual for Internal Corrosion of Water Distribution Systems

Oak Ridge National Lab., TN

Prepared for

Environmental Protection Agency, Washington, DC

Apr 84

U.S. Department of Commerce
National Technical Information Service
NTIS

TECHNICAL REPORT DATA

(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA 570/9-84-001

2.

3. RECIPIENT'S ACCESSION NO. PB84 21029 3

4. TITLE AND SUBTITLE
Corrosion Manual for Internal Corrosion of
Water Distribution Systems

5. REPORT DATE April 1984

6. PERFORMING ORGANIZATION CODE 45021005

7. AUTHOR(S) Environmental Science & Engineering, Inc.

8. PERFORMING ORGANIZATION REPORT NO.

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Environmental Science & Engineering, Inc.
Gainesville, Florida

10. PROGRAM ELEMENT NO. A634c2B

11. CONTRACT/GRANT NO.

12. SPONSORING AGENCY NAME AND ADDRESS
U.S. Environmental Protection Agency
Office of Drinking Water (WH-550)
Criteria & Standards Division
Washington, D.C. 20460

13. TYPE OF REPORT AND PERIOD COVERED Technical

14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

16. ABSTRACT

Corrosion of distribution piping and of home plumbing and fixtures has been estimated to cost the public water supply industry more than $700 million per year. Two toxic metals that occur in tap water, almost entirely because of corrosion, are lead and cadmium. Three other metals, usually present because of corrosion, cause staining of fixtures, metallic taste, or both. These are copper (blue stains and metallic taste), iron (red-brown stains and metallic taste), and zinc (metallic taste).

This manual was written to give the operators of potable water treatment plants and distribtuion systems an understanding of the causes and control of corrosion. The many types of corrosion and the types of materials with which the water comes in contact make the problem more complicated. Because all operators have not had the opportunity to gain more than a basic understanding of chemestry and engineering, there is little of these disciplines included in the document.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
corrosion potable water supplies drinking water water treatment		

18. DISTRIBUTION STATEMENT Open

19. SECURITY CLASS (This Report) Non-sensitive

20. SECURITY CLASS (This page)

21. NO. OF PAGES 142

22. PRICE

EPA Form 2220-1 (Rev. 4-77) PREVIOUS EDITION IS OBSOLETE

United States
Environmental Protection
Agency

Office of
Drinking Water (WH-550)
Washington, DC 20460

EPA 570/9-84-001
April 1984

PB84-210293

EPA

Corrosion Manual for Internal Corrosion of Water Distribution Systems

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

ORNL/TM-8919

CORROSION MANUAL FOR INTERNAL CORROSION OF WATER DISTRIBUTION SYSTEMS

Prepared for

U.S. ENVIRONMENTAL PROTECTION AGENCY
Washington, D.C.
Peter Lassovszky, Project Officer

Prepared by

ENVIRONMENTAL SCIENCE AND ENGINEERING, INC.

J.E. Singley
B.A. Beaudet
P.H. Markey

Gainesville, Florida

Under subcontract to

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee

ESE No. 81-227-260

April 1984

i.b

ATTENTION

AS NOTED IN THE NTIS ANNOUNCEMENT, PORTIONS OF THIS REPORT ARE NOT LEGIBLE. HOWEVER, IT IS THE BEST REPRODUCTION AVAILABLE FROM THE COPY SENT TO NTIS.

DISCLAIMER

This manual has been reviewed by the U.S. Environmental Protection Agency and approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation of their use.

CONTENTS

LIST OF FIGURES v

LIST OF TABLES vii

PREFACE ix

ACKNOWLEDGMENTS xi

ACRONYMS xiii

1.0 PURPOSE 1

2.0 INTRODUCTION 3

3.0 DEFINITION OF CORROSION AND BASIC THEORY 7

- 3.1 DEFINITION 7
- 3.2 BASIC THEORY 7
- 3.3 CHARACTERISTICS OF WATER THAT AFFECT CORROSIVITY 11

4.0 MATERIALS USED IN DISTRIBUTION SYSTEMS 19

5.0 RECOGNIZING THE TYPES OF CORROSION 25

6.0 CORROSION MONITORING AND TREATMENT 41

- 6.1 INDIRECT METHODS 41
- 6.2 DIRECT METHODS 54

7.0 CORROSION CONTROL 61

- 7.1 PROPER SELECTION OF SYSTEM MATERIALS AND ADEQUATE SYSTEM DESIGN 61
- 7.2 MODIFICATION OF WATER QUALITY 63
- 7.3 USE OF INHIBITORS 67
- 7.4 CATHODIC PROTECTION 70
- 7.5 LININGS, COATINGS, AND PAINTS 70
- 7.6 REGULATORY CONCERNS IN THE SELECTION OF PRODUCTS USED FOR CORROSION CONTROL 72

8.0 CASE HISTORIES 77

- 8.1 PINELLAS COUNTY WATER SYSTEM 77
- 8.2 MANDARIN UTILITIES 83
- 8.3 MIDDLESEX WATER COMPANY 85
- 8.4 SMALL HOSPITAL SYSTEM 88
- 8.5 BOSTON METROPOLITAN AREA WATER SYSTEM 90
- 8.6 GALVANIZED PIPE AND THE EFFECTS OF COPPER 95
- 8.7 GREENWOOD, SOUTH CAROLINA 96

9.0 COSTS OF CORROSION CONTROL 101

- 9.1 MONITORING COSTS 101
- 9.2 CONTROL COSTS 102

GLOSSARY 105

ADDITIONAL SOURCE MATERIALS 111

LIST OF FIGURES

Figure

3.1 Simplified anode and cathode reactions of iron in contact with water ... 8
3.2 Role of oxygen in iron corrosion ... 10
3.3 Simplified galvanic cell ... 10
3.4 Inside of hot-water heater destroyed by pitting ... 13
5.1 Galvanic corrosion resulting from a galvanized pipe joined to a copper pipe by a brass elbow ... 26
5.2 Galvanic corrosion illustrated by severely corroded galvanized steel nipple in a brass elbow ... 27
5.3 Pitting of steel pipe ... 29
5.4 Pitted red brass (85% copper) pipe from a domestic hot-water system ... 30
5.5 Tuberculation in a cast iron pipe ... 31
5.6 Galvanized steel pipe from a domestic hot-water system showing almost complete clogging by corrosion products ... 32
5.7 Tuberculation in a cast iron pipe ... 33
5.8 Erosion corrosion of yellow brass impeller from domestic hot-water circulation pump ... 34
5.9 Cavitation corrosion of brass impeller ... 35
5.10 Extreme example of stray current corrosion in an outside water faucet caused by lightning leaving the pipe ... 36
5.11 Dezincification of yellow brass in domestic water pipe ... 37
6.1 Sample questionnaire ... 42
6.2 Excessive $CaCO_3$ scaling resulting in loss of carrying capacity ... 44
6.3 Graphic representation of the various degrees of corrosion and encrustation ... 49
7.1 Steps toward solving corrosion problems ... 62
7.2 Schematic of a chemical feed system ... 66
7.3 Commercially available phosphate or silicate feed system ... 69
8.1 Inhibitor pilot test ... 80
8.2 Coupon corrosion rates of NaOH and inhibitors ... 81
8.3 Coupon testing cell assembly ... 87
8.4 Schematic of inhibitor installation ... 89
8.5 Mean lead levels from samples taken in Boston and Sommerville, Massachusetts, 1976-1981 ... 93

8.6 Water temperature, Metropolitan District Commission, Norumbega Reservoir 93
8.7 Mean copper levels from samples taken in Boston and Sommerville, Massachusetts, 1976-1981 94
8.8 Mean iron levels from samples taken in Boston and Sommerville, Massachusetts, 1976-1981 95

LIST OF TABLES

Table

3.1 Galvanic series — Order of activity of common metals used in water distribution systems 8

3.2 Chemical factors influencing corrosion and corrosion control 14

4.1 Common materials found in water supply systems and their uses 19

4.2 Corrosion properties of frequently used materials in water distribution systems 20

6.1 Typical customer complaints due to corrosion 41

6.2 Constant "A" as function of water temperature 45

6.3 Constant "B" as function of total filterable residue 46

6.4 Logarithms of calcium and alkalinity concentrations 46

6.5 Corrosivity of waters versus the Langelier Saturation Index (LSI) 48

6.6 Summary of corrosion indices 50

6.7 1980 Amendments to the NIPDWR: Sampling and analytical requirements 51

6.8 Recommended analyses for a thorough corrosion monitoring program 53

6.9 Water quality data from a Florida water utility 54

7.1 Chemicals for pH adjustment and/or carbonate supplementation 65

7.2 Pipe wall linings 71

7.3 Water storage tank linings and coatings 72

8.1 PCWS typical effluent water analysis 78

8.2 Mandarin utilities' finished water quality at Pickwick Park prior to aeration installation 84

8.3 Average water analyses 86

8.4 Metropolitan District Commission water quality data 91

8.5 Sampling instructions 92

8.6 Greenwood, South Carolina water quality data 96

9.1 Cost of typical analytical services for drinking water (1982) 102

9.2 Typical annual chemical costs for corrosion control (1982) 104

PREFACE

The U.S. Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled water are tragic testimonies to the deterioration of our natural environment. The complexity of that environment and the interplay of its components require a concentrated and integrated attack on the problem.

The Safe Drinking Water Act of 1974 represents the first national commitment to provide safe drinking water to the public. The National Interim Primary Drinking Water Regulations describe the maximum allowable contaminant levels for a variety of pollutants in drinking water that may adversely affect the health of the consumer. The National Secondary Drinking Water Regulations deal with the aesthetic qualities of drinking water such as taste, odor, color, and appearance, which, if substandard, could deter public acceptance of potable water provided by public water systems.

Corrosion in water supply distribution systems is a very significant concern because it not only affects the aesthetic quality of the water but also it has an economic impact and poses adverse health implications. Corrosion by-products containing materials such as lead and cadmium have been associated with serious risks to the health of consumers of drinking water. In addition, corrosion-related contaminants commonly include compounds such as zinc, iron, and copper, which adversely affect the aesthetic aspects of the water. This manual provides information about the causes and types of corrosion as well as practical guidance to water suppliers and operators of water treatment facilities for detecting and solving corrosion-related problems.

Victor Kimm, Director
Office of Drinking Water
U.S. Environmental Protection Agency

ACKNOWLEDGMENTS

This manual was prepared by Environmental Science and Engineering, Inc. (ESE) of Gainesville, Florida. Dr. J. Edward Singley was Project Director and Senior Technical Advisor; Mr. Bevin A. Beaudet, P.E., was Project Manager; and Ms. Patricia H. Markey was Project Engineer. During the preparation of the manual, invaluable technical review and input were received from several individuals and agencies.

Appreciation is expressed to the Office of Drinking Water, U.S. Environmental Protection Agency (EPA), most particularly to Mr. Peter Lassovszky, Project Officer, for his direction and guidance through all stages of the writing.

Each draft of the manual was reviewed by a Blue Ribbon Panel of experts selected for their expertise and knowledge in the field of corrosion of potable water distribution systems. Special acknowledgment is due the following individuals, who served on this panel:

> Mr. Russell W. Lane, P.E., Water Treatment Consultant; former head of the Illinois State Water Survey and professor, University of Illinois, Urbana-Champaign, Illinois.
>
> Dr. Frank J. Baumann, Chief, Southern California Branch Laboratory Section of the Los Angeles Department of Health Services, Los Angeles, California.
>
> Mr. Douglas Corey, South Dade Utilities, Miami, Florida; 1982 President of Florida Water and Pollution Control Operators Association, Inc.

Appreciation is expressed to Dr. Sidney Sussman, Technical Director of Olin Water Services for supplying several of the example photographs throughout the manual and for his contribution to the inhibitor treatment material in Section 7. Mr. Thomas F. Flynn, P.E., President of Shannon Chemical also supplied valuable input to the section on inhibitor treatment. Dr. Jiterdra Saxena and Arthur Perler, Office of Drinking Water, provided a section on regulatory aspects associated with the use of inhibitors.

Acknowledgment is also due members of the American Water Works Association (AWWA) Research Foundation and individuals from EPA who reviewed the manual and provided technical assistance and input. Individuals deserving particular mention are Mr. James F. Manwaring, P.E., Executive Director, AWWA Research Foundation; Dr. Marvin Gardels, Mr. Michael R. Schock, and Dr. Gary S. Logsdon, from EPA Cincinnati; Mr. Peter Karalekas, P.E., EPA Region I; Dr. Mark A. McClanahan, EPA Region IV; Mr. Harry Von Huben, EPA Region V; Mr. Roy Jones, EPA Region X; and Mr. Hugh Hanson, Chief, Science and Technology Branch, Criteria and Standards Division, Office of Drinking Water, EPA.

Appreciation is also expressed to Dr. Joseph A. Cotruvo, Director, and Mr. Craig Vogt, Deputy Director, Criteria and Standards Division, Office of Drinking Water, EPA, for their support.

ACRONYMS

A-C	asbestos-cement
AI	Aggressive Index
ASTM	American Society for Testing and Materials
AWWA	American Water Works Association
CI	Riddick's Corrosion Index
CPW	Commissioners of Public Works
DFI	McCauley's Driving Force Index
DO	dissolved oxygen
DWRD	Drinking Water Research Division
EPA	U.S. Environmental Protection Agency
ESE	Environmental Science and Engineering, Inc.
ISWS	Illinois State Water Survey
LSI	Langelier Saturation Index
MCL	maximum contaminant level
MDC	Metropolitan District Commission
MWC	Middlesex Water Company
NACE	National Association of Corrosion Engineers
NAS	National Academy of Sciences
NIPDWR	National Interim Primary Drinking Water Regulations
ODW	Office of Drinking Water
ORNL	Oak Ridge National Laboratory
PCWS	Pinellas County Water System
PVC	polyvinyl chloride
RMICs	recommended maximum impurity concentrations
RSI	Ryznar Stability Index
SEM	scanning electron microscope
TDS	total dissolved solids

FREQUENTLY USED UNITS AND OTHER TERMS

MGD	million gallons per day
$CaCO_3$	calcium carbonate
H_2S	hydrogen sulfide
CO_2	carbon dioxide
NaOH	sodium hydroxide
SZP	sodium zinc phosphate
ZOP	zinc orthophosphate
gpm	gallons per minute
CaO	quicklime
mpy	mils per year
mg/cm^2	milligrams per centimeter square
mg/L	milligrams per liter

ORNL-DWG 83C-19668

CORROSION MANUAL FOR INTERNAL CORROSION OF WATER DISTRIBUTION SYSTEMS
INDEX

PURPOSE p. 1
INTRODUCTION p. 3
DEFINITION OF CORROSION AND BASIC THEORY p. 7
MATERIALS USED IN DISTRIBUTION SYSTEMS p. 19
RECOGNIZING THE TYPES OF CORROSION p. 25
CORROSION MONITORING AND MEASUREMENT p. 41
CORROSION CONTROL p. 61
CASE HISTORIES p. 77
COSTS OF CORROSION CONTROL p. 101

1.0 PURPOSE

This manual was written to give the operators of potable water treatment plants and distribution systems an understanding of the causes and control of corrosion. The many types of corrosion and the types of materials with which the water comes in contact make the problem more complicated. Because all operators have not had the opportunity to gain more than a basic understanding of chemistry and engineering, there is little of these disciplines included in the document.

The goal in writing the manual was to create a "how-to" guide that would contain additional information for those who want to study corrosion in more detail. Sections 3.0, 4.0, and 5.0 can be skipped in cases in which an immediate problem needs to be solved. Those sections, though, do help in understanding how and why corrosion occurs.

2.0 INTRODUCTION

Corrosion of distribution piping and of home plumbing and fixtures has been estimated to cost the public water supply industry more than $700 million per year. Two toxic metals that occur in tap water, almost entirely because of corrosion, are lead and cadmium. Three other metals, usually present because of corrosion, cause staining of fixtures, or metallic taste, or both. These are copper (blue stains and metallic taste), iron (red-brown stains and metallic taste), and zinc (metallic taste).

Since the Safe Drinking Water Act (P.L. 93-523) makes the supplying utility responsible for the water quality at the customer's tap, it is necessary to prevent these metals from getting into the water on the way to the tap.

The toxic metals lead and cadmium can cause serious health problems when present in quantities above the levels set by the National Interim Primary Drinkig Water Regulations (NIPDWR). The other metals—copper, iron, and zinc—are included in the Secondary Drinking Water Regulations because they cause the water to be less attractive to consumers and thus may cause them to use another, potentially less safe, source.

The corrosion products in the distribution system can also protect bacteria, yeasts, and other microorganisms. In a corroded environment, these organisms can reproduce and cause many problems such as bad tastes, odors, and slimes. Such organisms can also cause further corrosion themselves.

Corrosion-caused problems that add to the cost of water include

1. increased pumping costs due to corrosion products clogging the lines;
2. holes in the pipes, which cause loss of water and water pressure;
3. leaks and clogs, as well as water damage to the dwelling, which would require that pipes and fittings be replaced;
4. excessive corrosion, which would necessitate replacing hot water heaters; and
5. responding to customer complaints of "colored water," "stains," or "bad taste," which is expensive both in terms of money and public relations.

Corrosion is one of the most important problems in the water utility industry. It can affect public health, public acceptance of a water supply, and the cost of providing safe water. Many times the problem is not given the attention it needs until expensive changes or repairs are required.

Both the Primary and Secondary Regulations recognize that corrosion is a serious concern. However, the lack of a universal measurement or index for corrosivity has made it difficult to regulate. The United States Environmental Protection Agency (EPA) recognizes that corrosion problems are unique to each individual water supply system. As a result, the August 1980 amendments to the NIPDWR issued by EPA concentrate on identifying both potentially corrosive waters and finding out what materials are in distribution systems. The 1980 amendments to the regulations require that

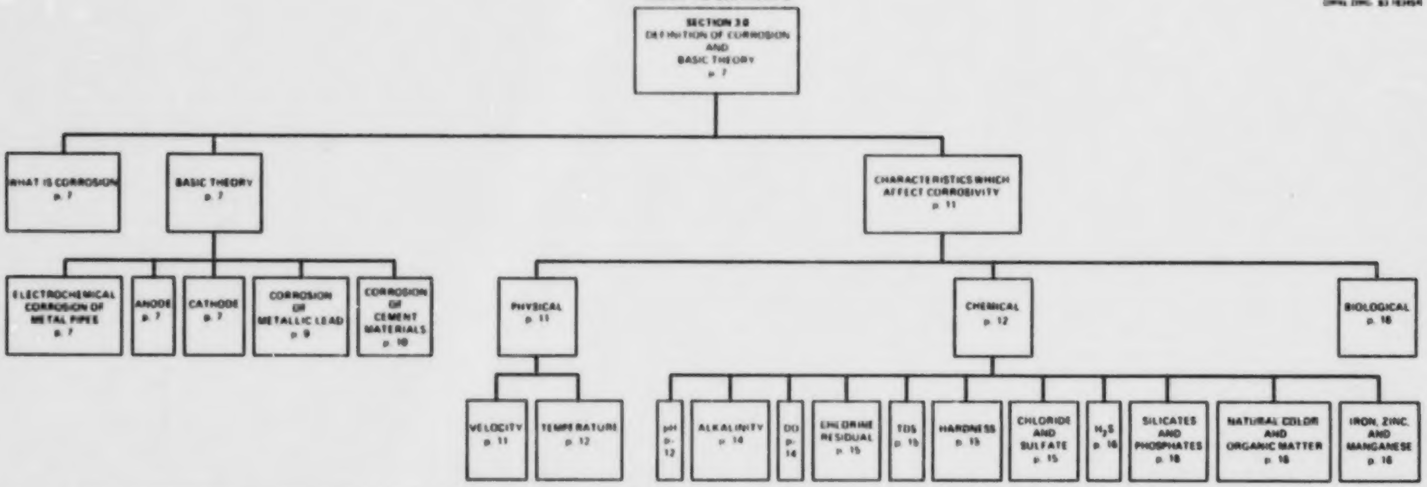
1. All community water supply systems collect and analyze samples for the following corrosion characteristics: alkalinity, pH, hardness, temperature, total dissolved solids (TDS), and Langelier Saturation Index (LSI) [or Aggressive Index (AI) in certain cases]. "Corrosivity characteristics" need to be monitored and reported only once, unless individual states require additional sampling.
2. The samples be taken at a representative point in the distribution system. Two samples are to be taken within 1 year from each treatment plant, using a surface water source to account for extremes in seasonal variations. One sample per plant is required for plants using groundwater sources.

Preceding page blank

3. Community water supply systems identify whether the following construction materials are present in their distribution system, including service lines and home plumbing, and report their findings to the state: (a) lead from piping, solder, caulking, interior lining of distribution mains, alloys, and home plumbing; (b) copper from piping and alloys, service lines, and home plumbing; (c) galvanized piping, service lines, and home plumbing; (d) ferrous piping materials, such as cast iron and steel; and (e) asbestos-cement (A-C) pipe.

   In addition, states may require the identification and reporting of other construction materials present in distribution systems that may contribute contaminants to the drinking water, such as (f) vinyl-lined A-C pipe and (g) coal tar-lined pipes and tanks.

INDEX TO SECTION 3


SECTION 3.0
DEFINITION OF CORROSION AND BASIC THEORY p. 7
WHAT IS CORROSION p. 7
BASIC THEORY p. 7
CHARACTERISTICS WHICH AFFECT CORROSIVITY p. 11
ELECTROCHEMICAL CORROSION OF METAL PIPES p. 7
ANODE p. 7
CATHODE p. 7
CORROSION OF METALLIC LEAD p. 9
CORROSION OF CEMENT MATERIALS p. 10
PHYSICAL p. 11
CHEMICAL p. 12
BIOLOGICAL p. 16
VELOCITY p. 11
TEMPERATURE p. 12
pH p. 12
ALKALINITY p. 14
DO p. 14
CHLORINE RESIDUAL p. 15
TDS p. 15
HARDNESS p. 15
CHLORIDE AND SULFATE p. 15
H_2S p. 16
SILICATES AND PHOSPHATES p. 16
NATURAL COLOR AND ORGANIC MATTER p. 16
IRON, ZINC, AND MANGANESE p. 16

3.0 DEFINITION OF CORROSION AND BASIC THEORY

3.1 DEFINITION

What is corrosion?

Corrosion is the deterioration of a substance or its properties due to a reaction with its environment. In the waterworks industry, the "substance" which deteriorates may be a metal pipe or fixture, the cement in a pipe lining, or an asbestos-cement (A-C) pipe. For internal corrosion, the "environment" of concern is water.

A common question is, "What type of water causes corrosion?" The correct answer is, "All waters are corrosive to some degree." A water's corrosive tendency will depend on its physical and chemical characteristics. Also, the nature of the material with which the water comes in contact is important. For example, water corrosive to galvanized iron pipe may be relatively noncorrosive to copper pipe in the same system.

3.2 BASIC THEORY

Physical and chemical actions between pipe material and water may cause corrosion. An example of a physical action is the erosion or wearing away of a pipe elbow because of excess flow velocity in the pipe. An example of a chemical action is the oxidation or rusting of an iron pipe. Biological growths in a distribution system can also cause corrosion by providing a suitable environment in which physical and chemical actions can occur. The actual mechanisms of corrosion in a water distribution system are usually a complex and interrelated combination of these physical, chemical, and biological actions.

Following is a discussion of the basic chemical reactions which cause corrosion in water distribution systems, for both metallic and nonmetallic pipes. Familiarity with these basic reactions will help users recognize and correct corrosion problems associated with water utilities.

A more detailed, yet relatively basic, discussion of the theory of corrosion can be found in an excellent book titled *NACE Basic Corrosion Course*, published by the National Association of Corrosion Engineers (NACE), which is now in its fifth printing.

Electrochemical Corrosion of Metal Pipes

Metals are generally most stable in their natural form. In most cases, this stable form is the same form in which they occur in native ores and from which they are extracted in processing. Iron ore, for instance, is essentially a form of iron oxide, as is rust from a corroded iron pipe. The primary cause of metallic corrosion is the tendency (also called activity) of a metal to return to its natural state. Some metals are more active than others and have a greater tendency to enter into solution as ions and to form various compounds. Table 3.1 lists the relative order of activity of several commonly used metals and alloys. Such a listing is also called a "galvanic series," for reasons which are discussed below.

When metals are chemically corroded in water, the mechanism involves some aspect of electrochemistry. When a metal goes into solution as an ion or reacts in water with another element to form a compound, electrons (electricity) will flow from certain areas of a metal surface to other areas through the metal.

The term "anode" is used to describe that part of the metal surface that is corroded and from which electric current, as electrons, flows through the metal to the other electrode. The term "cathode" is used to describe the metal surface from which current, as ions, leaves the metal and returns to the anode through the solution. Thus, the circuit is completed. All water solutions will conduct a current. "Conductivity" is a measure of that property.

Figure 3.1 is a simplified diagram of the anodic and cathodic reactions that occur when iron is in contact with water. The anode and cathode areas may be located in different areas of the pipe, as shown in Fig. 3.1, or they can be located right next to each other. The anode and cathode areas

Preceding page blank

Table 3.1. Galvanic series — Order of activity of common metals used in water distribution systems

Metal	Activity
Zinc	More active
Mild steel	↑
Cast iron	|
Lead	|
Brass	|
Copper	|
Stainless steel	Less active

Source: Environmental Science and Engineering, Inc., 1982.

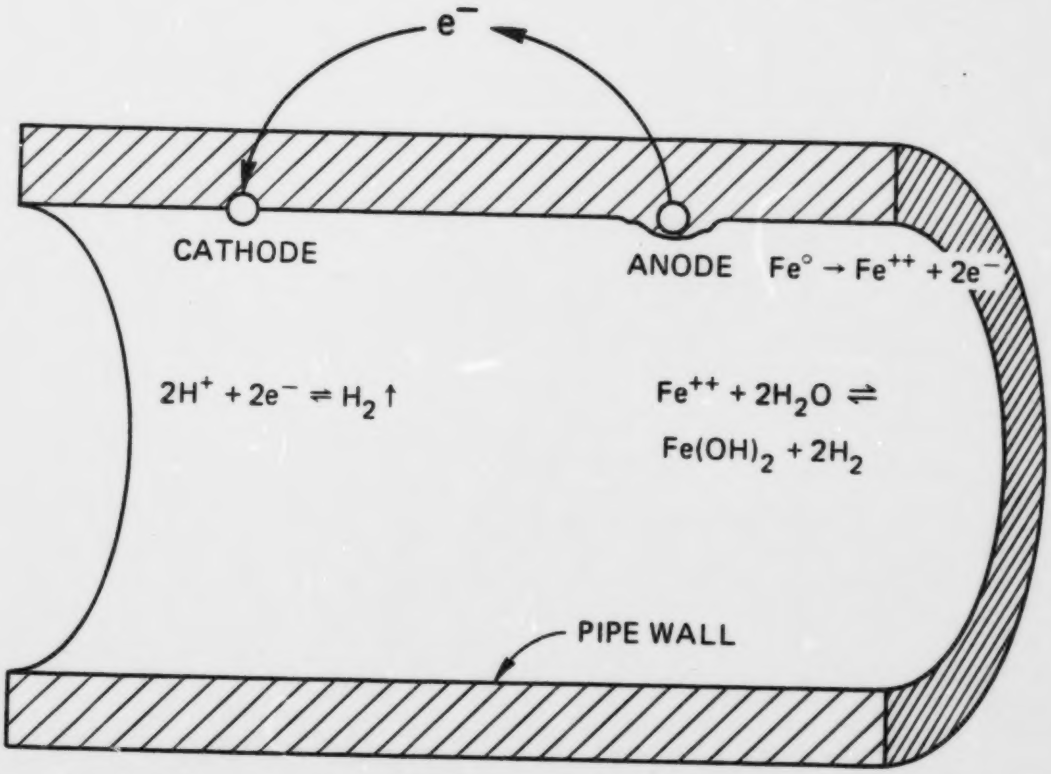

ORNL DWG 83-17055
e⁻
CATHODE
ANODE
Fe° → Fe⁺⁺ + 2e⁻
2H⁺ + 2e⁻ ⇌ H₂ ↑
Fe⁺⁺ + 2H₂O ⇌
Fe(OH)₂ + 2H₂
PIPE WALL

Fig. 3.1. Simplified anode and cathode reactions of iron in contact with water. Source of H^+ ions is the normal dissociation of water, $H_2O \rightleftharpoons H^+ + OH^-$.

can set up a circuit in the same metal or between two different metals which are connected. In the case of iron corrosion, as the free iron metal goes into solution in the form FE^{++} (ferrous) ion at the anode, two electrons are released. These electrons, having passed through the metal pipe, combine at the cathode with H$^+$ (hydrogen) ions that are always present due to the normal dissociation of water, according to ($H_2O \rightleftharpoons H^+ + OH^-$). This action forms hydrogen gas, which collects on the cathode and thus slows the reaction (polarization). The Fe^{++} ions released at the anode react further with the water to form ferrous hydroxide, $Fe(OH)_2$.

Oxygen plays a major role in the internal corrosion of water distribution systems. Oxygen dissolved in water reacts with the initial corrosion reaction products at both the anodic and cathodic regions. Ferrous (iron II) hydroxide formed at the anode reacts with oxygen to form ferric (iron III) hydroxide, $Fe(OH)_3$, or rust. Oxygen also reacts with the hydrogen gas evolved at the cathode to form water, thus allowing the initial anodic reaction to continue (depolarization).

The simplified equations that describe the role of oxygen in aiding iron corrosion are shown below. Similar equations could be shown for copper or other corroding metals. Equations (1) and (2) are for anodic reactions and Eq. (3) shows cathodic reactions.

$$\underset{\text{ferrous iron}}{4Fe^{++}} + \underset{\text{water}}{10H_2O} + \underset{\text{free oxygen}}{O_2} \rightarrow \underset{\text{ferric hydroxide}}{4Fe(OH)_3} + \underset{\text{hydrogen}}{8H^+} \qquad (1)$$

or

$$\underset{\text{ferrous hydroxide}}{4Fe(OH)_2} + \underset{\text{water}}{2H_2O} + \underset{\text{free oxygen}}{O_2} \rightarrow \underset{\text{ferric hydroxide}}{4Fe(OH)_3} \qquad (2)$$

$$\underset{\text{hydrogen}}{4H^+} + \underset{\text{electrons}}{4e} + \underset{\text{oxygen}}{O_2} \rightarrow \underset{\text{water}}{2H_2O} \qquad (3)$$

The importance of dissolved oxygen (DO) in corrosion reactions of iron pipe is shown in Fig. 3.2.

A similar electrochemical reaction occurs when two dissimilar metals are in direct contact in a conducting solution. Such a connection is commonly called a "galvanic couple." An example of a galvanic couple would be a ductile iron nipple used to connect two pieces of copper pipe. In this case, the more active metal, iron, would corrode at the anode and give up electrons to the cathode. The net effect would be a slowing down or stopping of copper corrosion and an acceleration of iron corrosion where the metals are in contact. Figure 3.3 illustrates a typical galvanic cell. In addition, the farther apart the two dissimilar metals are in the galvanic series (see Table 3.1), the greater the corrosive tendencies. For example, a copper-to-zinc connection would be more likely to corrode than a copper-to-brass connection.

Corrosion of Metallic Lead

Metallic lead can be present in distribution systems either in the form of lead service pipes, found in many older systems, or in lead/tin solder used to join copper household plumbing. Lead is a stable metal of relatively low solubility and is structurally resistant to corrosion. However, the toxic effects of lead are pronounced [the NIPDWR maximum contaminant level (MCL) for lead is 0.05 milligram per liter (mg/L)]. Thus, even low levels of lead corrosion may be of major concern.

Metallic lead is frequently protected from corrosion by a thin layer of insoluble lead carbonates that forms on the surface of the metal. The solubility of metallic lead (plumbosolvency) is complicated and is related to the pH and the carbonate content (alkalinity) of the water. Consistent control of pH in the presence of sufficient alkalinity will generally minimize plumbosolvency in water distribution systems.

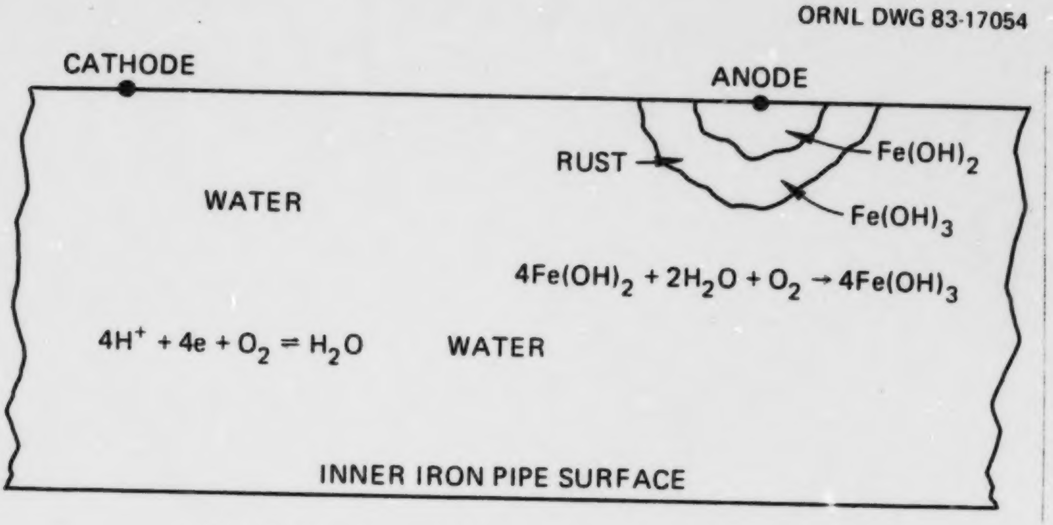

ORNL DWG 83-17054
CATHODE
ANODE
RUST
$Fe(OH)_2$
$Fe(OH)_3$
WATER
$4Fe(OH)_2 + 2H_2O + O_2 \rightarrow 4Fe(OH)_3$
$4H^+ + 4e + O_2 = H_2O$
WATER
INNER IRON PIPE SURFACE

Fig. 3.2. Role of oxygen in iron corrosion. Source: ESE, 1982.

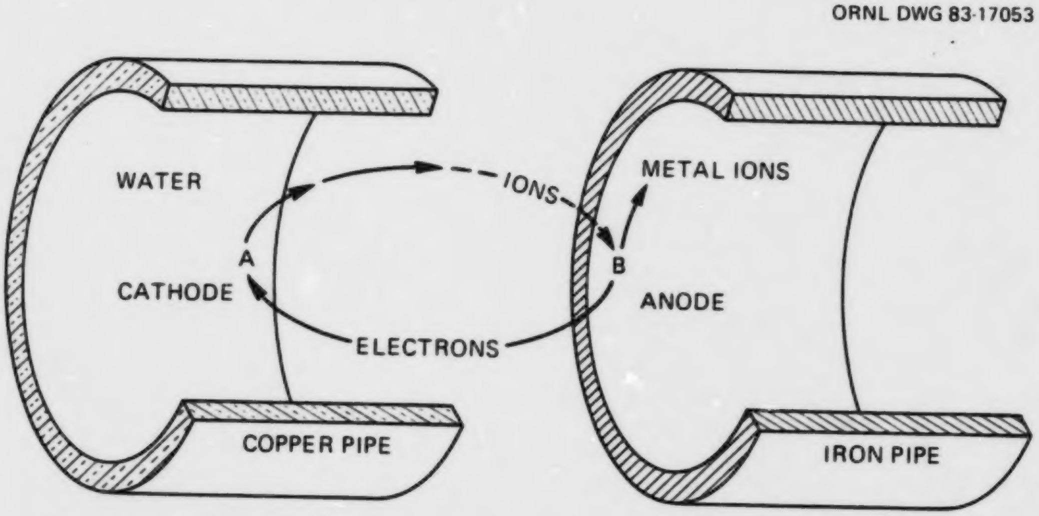

ORNL DWG 83-17053
WATER
IONS
METAL IONS
A
B
CATHODE
ANODE
ELECTRONS
COPPER PIPE
IRON PIPE

Fig. 3.3. Simplified galvanic cell. Note that areas A and B are located on the inner pipe surface.

Corrosion of Cement Materials

The corrosion of cement-lined pipe, concrete pipe, or A-C pipe is primarily a chemical reaction in which the cement is dissolved by water. Cement materials are made up of numerous, crystalline compounds which normally are hard, durable, and relatively insoluble in water.

Modern, autoclave-curved (Type II) A-C pipe is formed from a mixture of three main ingredients:

Ingredient	Percentage by weight
Asbestos fiber	15–20
Silica flour (ground sand or silicon dioxide)	34–37
Portland cement	51–48

The calcium-containing Portland cement serves as a binder, and the autoclaving process reduces free lime content to less than 1%. Silica flour acts as a reactive aggregate for the cement. The asbestos fibers give flexibility and structural strength to the finished product. When calcium is leached from the cement binder by the action of an aggressive (corrosive) water, the interior pipe surface is softened, and asbestos fibers may be released.

Type I A-C pipe was widely used before the 1950s and may be present in many older systems. Unlike Type II, Type I has no silica flour but contains 15 to 20% asbestos fibers, 80 to 85% Portland cement, and 12 to 20% free lime. Calcium leaching is more commonly observed in Type I A-C pipe.

The solubility of the calcium-containing cement compounds is pH dependent. At low pH (less than about 6.0), the leaching of these compounds from the pipe is much more pronounced than at a pH above 7.0. The solubility of a cement lining, concrete pipe, or an A-C pipe in a given water can be approximated by the tendency of that water to dissolve calcium carbonate ($CaCO_3$).

3.3 CHARACTERISTICS OF WATER THAT AFFECT CORROSIVITY

In Sect. 3.1, corrosion is defined as the deterioration of a material (or is properties) because of a reaction with its environment. In the waterworks industry, the materials of interest are the distribution and home water plumbing systems, and the environment that may cause internal pipe corrosion is drinking water.

For operators or managers of water utilities, the obvious question is, "What characteristics of this drinking water determine whether or not it is corrosive?" The answers to this question are important because waterworks personnel can control, to some extent, the characteristics of this drinking water environment.

Those characteristics of drinking water that affect the occurrence and rate of corrosion can be classified as (1) physical, (2) chemical, and (3) biological. In most cases, corrosion is caused or increased by a complex interaction among several factors. Some of the more common characteristics in each group are discussed in the following paragraphs to familiarize the reader with their potential effects. Controlling corrosion may require changing more than one of these because of their interrelationship.

Physical Characteristics

Flow velocity and temperature are the two main physical characteristics of water that affect corrosion.

Velocity. Flow velocity has seemingly contradictory effects. In waters with protective properties, such as those with scale-forming tendencies, high flow velocities can aid in the formation of protective coatings by transporting the protective material to the surfaces at a higher rate. However, high flow velocities are usually associated with erosion corrosion in copper pipes in which the protective wall coating or the pipe material itself is removed mechanically. High velocity waters combined with other corrosive characteristics can rapidly deteriorate pipe materials.

Another way in which high velocity flow can contribute to corrosion is by increasing the rate at which DO comes in contact with pipe surfaces. Oxygen often plays an important role in determining corrosion rates because it enters into many of the chemical reactions which occur during the corrosion process.

Extremely low velocity flows may also cause corrosion in water systems. Stagnant flows in water mains and household plumbing have occasionally been shown to promote tuberculation and pitting, especially in iron pipe, as well as biological growths. Therefore, one should avoid dead ends.

Proper hydraulic design of distribution and plumbing systems can prevent or minimize erosion corrosion of water lines. The NACE, the American Society for Testing and Materials (ASTM), and pipe manufacturers can provide guidance on design criteria for standard construction materials. A maximum value of 4 feet per second (ft/s), 9.8 gallons per minute (gal/min) in a 1-inch pipe for instance, is recommended for Type K copper tubing.

Temperature. Temperature effects are complex and depend on the water chemistry and type of construction material present in the system. Three basic effects of temperature change on corrosion rates are discussed here.

In general, the rate of all chemical reactions, including corrosion reactions, increases with increased temperature. All other aspects being equal, hot water should be more corrosive than cold. Water which shows no corrosive characteristics in the distribution system can cause severe damage to copper or galvanized iron hot water heaters at elevated temperatures. Figure 3.4 shows the inside of a water heater totally destroyed by pitting corrosion. The same water showed no corrosive characteristics in other parts of the distribution system.

Second, temperature significantly affects the dissolving of $CaCO_3$. Less $CaCO_3$ dissolves at higher temperatures, which means that $CaCO_3$ tends to come out of solution (precipitate) and form a protective scale more readily at higher temperatures. The protective coating resulting from this precipitation can reduce corrosion in a system. On the other hand, excessive deposition of $CaCO_3$ can clog hot water lines.

Finally, a temperature increase can change the entire nature of the corrosion. For example, a water which exhibits pitting at cold temperatures may cause uniform corrosion when hot. Although the total quantity of metal dissolved may increase, the attack is less acute, and the pipe will have a longer life. Another example in which the nature of the corrosion is changed as a result of changes in temperature involves a zinc-iron couple. Normally, the anodic zinc is sacrificed or corroded to prevent iron corrosion. In some waters, the normal potential of the zinc-iron couple may be reversed at temperatures above 140°F. In other words, the zinc becomes cathodic to the iron, and the corrosion rate of galvanized iron is much higher than is normally anticipated. Galvanized iron hot-water heaters can be especially susceptible to this change in potential at temperatures greater than 140°F.

Chemical characteristics

Most of the corrosion discussed in this manual involves the reaction of water with the piping. The substances dissolved in the water have an important effect on both corrosion and corrosion control. To understand these reactions thoroughly requires more knowledge of water chemistry than could be imparted here, but a brief overview will point out some of the most important factors. Table 3.2 lists some of the chemical factors that have been shown to have some effect on corrosion or corrosion control.

Several of these factors are closely related, and a change in one changes another. The most important example of this is the relationship between pH, carbon dioxide (CO_2), and alkalinity. Although it is frequently said that CO_2 is a factor in corrosion, no corrosion reactions include CO_2. The important corrosion effect results from pH, and pH is affected by a change in CO_2. It is not necessary to know all of the complex equations for these calculations, but it is useful to know that each of these factors plays some role in corrosion.

Following is a description of some of the corrosion-related effects of the factors listed in Table 3.2. A better understanding of their relationship to one another will aid in understanding corrosion and thus in choosing corrosion control methods.

pH. pH is a measure of the amount of hydrogen ions, H^+, present in water. Since H^+ is one of the major substances that accepts the electrons given up by a metal when it corrodes, pH is an important factor to measure. At pH values below about 5, both iron and copper corrode rapidly and uniformly. At values higher than 9, both iron and copper are usually protected. However, under certain conditions corrosion may be greater at high pH values. Between pH 5 and 9, pitting is likely to occur if no protective film is present. The pH also affects the formation or solubility of protective films, as will be discussed later.

Top 12a

Reproduced from
best available copy.

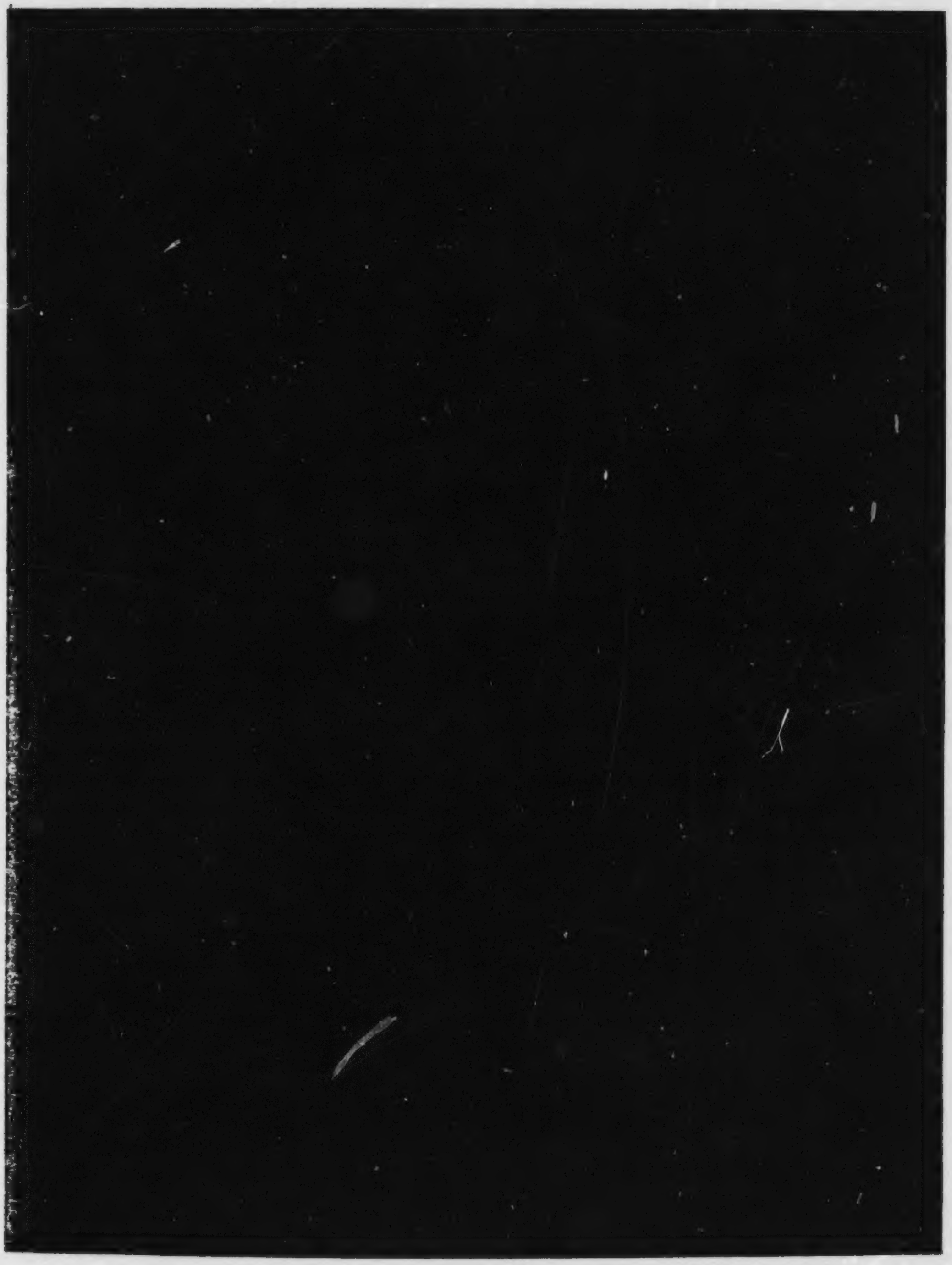


Fig. 3.4. Inside of hot-water heater destroyed by pitting.

Table 3.2. Chemical factors influencing corrosion and corrosion control

Factor	Effect
pH	Low pH may increase corrosion rate; high pH may protect pipes and decrease corrosion rates
Alkalinity	May help form protective $CaCO_3$ coating, helps control pH changes, reduces corrosion
DO	Increases rate of many corrosion reactions
Chlorine residual	Increases metallic corrosion
TDS	High TDS increases conductivity and corrosion rate
Hardness (Ca and Mg)	Ca may precipitate as $CaCO_3$ and thus provide protection and reduce corrosion rates
Chloride, sulfate	High levels increase corrosion of iron, copper, and galvanized steel
Hydrogen sulfide	Increases corrosion rates
Silicate, phosphates	May form protective films
Natural color, organic matter	May decrease corrosion
Iron, zinc, or manganese	May react with compounds on interior of A-C pipe to form protective coating

Source: Environmental Science and Engineering, Inc., 1982.

Alkalinity. Alkalinity is a measure of a water's ability to neutralize acids. In potable waters, alkalinity is mostly composed of carbonate, $CO_3^=$, and bicarbonates, HCO_3^-. The HCO_3^- portion of alkalinity can neutralize bases, also. Thus, the substances that normally contribute to alkalinity can neutralize acids, and any bicarbonate can neutralize bases. This property is called "buffering," and a measure of this property is called the "buffer capacity." Carbonate does not provide any buffer capacity for bases because it has no H^+ to react with the base. Buffer capacity can best be understood as resistance to change in pH.

The bicarbonate and carbonates present affect may important reactions in corrosion chemistry, including a water's ability to lay down a protective metallic carbonate coating. They also affect the concentration of calcium ions that can be present, which, in turn, affects the dissolving of calcium from cement-lined pipe or from A-C pipe. Alkalinity also reduces the dissolution of lead from lead pipes or lead-based solder by forming a protective coating of lead carbonate on the metallic surface.

DO. According to many corrosion experts, oxygen is the most common and the most important corrosive agent. In many cases, it is the substance that accepts the electrons given up by the corroding metal according to the following equation:

$$\begin{array}{ccccccc} O_2 & + & 2H_2O & + & 4e & \rightarrow & 4OH^- \\ \text{free oxygen} & + & \text{water} & + & \text{electrons} & \rightarrow & \text{hydroxide ions} \end{array} \quad (4)$$

and so allows the corrosion reactions to continue.

Oxygen also reacts with hydrogen, H_2, released at the cathode. This reaction removes hydrogen gas from the cathode and allows the corrosion reactions to continue. The equation is

$$\begin{array}{ccccc} 2H_2 & + & O_2 & \rightarrow & 2H_2O \\ \text{hydrogen} & + & \text{free oxygen} & \rightarrow & \text{water} \end{array} \tag{5}$$

Hydrogen gas (H_2) usually covers the cathode and retards further reaction. This is called polarization of the cathode. The removal of the H_2 by the above reaction is called depolarization.

Oxygen also reacts with any ferrous iron ions and converts them to ferric iron. Ferrous iron ions, Fe^{+2}, are soluble in water, but ferric iron forms an insoluble hydroxide. Ferric iron accumulates at the point of corrosion, forming a tubercle, or settles out at some point in the pipe and interferes with flow. The reactions are

$$\begin{array}{ccccc} Fe & \rightarrow & Fe^{2+} & + & 2e \\ \text{metallic iron} & \rightarrow & \text{ferrous iron} & + & \text{2 electrons} \end{array} \tag{6}$$

$$\begin{array}{ccccccc} 4Fe^{2+} & + & 3O_2 & + & 6H_2O & \rightarrow & 4Fe(OH)_3 \\ \text{ferrous iron} & + & \text{free oxygen} & + & \text{water} & \rightarrow & \text{ferric hydroxide} \\ & & & & & & \text{(insoluble)} \end{array} \tag{7}$$

When oxygen *is* present in water, tuberculation or pitting corrosion may take place. The pipes are affected both by the pits and by the tubercles and deposits. "Red water" may also occur, if velocities are sufficiently high to cause iron precipitates to be flushed out. In many cases when oxygen is not present, any corrosion of iron is usually noticed by the customer as "red water," because the soluble ferrous iron is carried along in the water, and the last reaction happens only after the water leaves the tap and is exposed to the oxygen in the air.

In some cases, oxygen may react with the metal surface to form a protective coating of the metal oxide.

Chlorine residual. Chlorine lowers the pH of the water by reacting with the water to form hydrochloric acid and hypochlorous acid:

$$\begin{array}{ccccccc} Cl_2 & + & H_2 & \rightarrow & HCl & + & HOCl \\ \text{chlorine} & + & \text{water} & \rightarrow & \text{hydrochloric acid} & + & \text{hypochlorous acid} \end{array} \tag{8}$$

This reaction makes the water potentially more corrosive. In waters with low alkalinity, the effect of chlorine on pH is greater because such waters have less capacity to resist pH changes. Tests show that the corrosion rate of steel is increased by free chlorine concentrations greater than 0.4 mg/L. Chlorine can act as a stronger oxidizing agent than oxygen in neutral (pH 7.0) waters.

Total dissolved solids (TDS). Higher TDS indicate a high ion concentration in the water, which increases conductivity. This increased conductivity in turn increases the water's ability to complete the electrochemical circuit and to conduct a corrosive current. The dissolved solids may affect the formation of protective films.

Hardness. Hardness is caused predominantly by the presence of calcium and magnesium ions and is expressed as the equivalent quantity of $CaCO_3$. Hard waters are generally less corrosive than soft waters if sufficient calcium ions and alkalinity are present to form a protective $CaCO_3$ lining on the pipe walls.

Chloride and sulfate. These two ions, Cl^- and $SO_4^=$, may cause pitting of metallic pipe by reacting with the metals in solution and causing them to stay soluble, thus preventing the formation of protective metallic oxide films. Chloride is about three times as active as sulfate in this effect. The ratio of the chloride plus the sulfate to the bicarbonate ($Cl^- + SO_4^=/HCO_3^-$) has been used by some corrosion experts to estimate the corrosivity of a water.

Hydrogen sulfide (H_2S). H_2S accelerates corrosion by reacting with the metallic ions to form insoluble sulfides. It attacks iron, steel, copper, and galvanized piping to form "black water," even in the absence of oxygen. An H_2S attack is often complex, and its effects may either begin immediately or may not become apparent for months and then will become suddenly severe.

Silicates and phosphates. Silicates and phosphates can form protective films which reduce or inhibit corrosion by providing a barrier between the water and the pipe wall. These chemicals are usually added to the water by the utility.

Natural color and organic matter. The presence of naturally occurring organic color and other organic substances may affect corrosion in several ways. Some natural organics can react with the metal surface and provide a protective film and reduce corrosion. Others have been shown to react with the corrosion products to increase corrosion. Organics may also tie up calcium ions and keep them from forming a protective $CaCO_3$ coating. In some cases, the organics have provided food for organisms growing in the distribution system. This can increase the corrosion rate in instances in which those organisms attack the surface as discussed in the section on biological characteristics. It has not been possible to tell which of these instances will occur for any specific water, so using color and organic matter as corrosion control methods is not recommended.

Iron, zinc, and manganese. Soluble iron, zinc and—to some extent—manganese, have been shown to play a role in reducing the corrosion rates of A-C pipe. Through a reaction which is not yet fully understood, these metallic compounds may combine with the pipe's cement matrix to form a protective coating on the surface of the pipe. Waters that contain natural amounts of iron have been shown to protect A-C pipe from corrosion. When zinc is added to water in the form of zinc chloride or zinc phosphate, a similar protection from corrosion has been demonstrated.

Biological Characteristics

Both aerobic and anaerobic bacteria can induce corrosion. Two common "corrosive" bacteria in water supply systems are iron-oxidizing and sulfate-reducing bacteria. Each can aid in the formation of tubercles in water pipes by releasing by-products which adhere to the pipe walls. In studies performed at the Columbia, Missouri, water distribution system, both sulfate-reducing and sulfur-oxidizing organisms were found where "red-water" problems were common.

Many organisms form precipitates with iron. Their activity can result in higher iron concentrations at certain points in the distribution system due to precipitation, as well as bioflocculation of the organisms.

Controlling these organisms can be difficult because many of the anaerobic bacteria exist under tubercles, where neither chlorine nor oxygen can get to them. In addition, they normally occur in dead ends or low-flow areas, in which a chlorine residual is not present or cannot be maintained.

ORNL-DWG 83-18346R

INDEX TO SECTION 4

SECTION 4.0 MATERIALS USED IN DISTRIBUTION SYSTEMS p. 19

- RELATIONSHIP OF PIPE MATERIAL TO CORROSION p. 19
- COMMON TYPES OF MATERIALS IN WATER SUPPLY SYSTEMS p. 19
- CORROSION RESISTANCE AND POTENTIAL CONTAMINANTS FROM MATERIALS p. 20
- METHODS OF IDENTIFYING CORROSION p. 21

4.0 MATERIALS USED IN DISTRIBUTION SYSTEMS

This section discusses the types of materials commonly used by the waterworks industry for distribution and home service lines. Why should utility managers or operators be concerned with the materials used in their water distribution system? First, because the use of certain pipe materials in a system can affect both corrosion rates and the kind of contaminants or corrosion products added to the water. Second, because properly selected materials used to replace existing lines or to construct new ones can significantly reduce corrosion activity.

Another important reason to identify materials used in a distribution system is that certain types of construction materials in the system can affect the type of corrosion control program which should be used to reduce or prevent corrosion in the system. Control measures successful for A-C pipe may not be successful for copper pipe. When the system contains several different materials, care must be taken to prevent control measures used to reduce corrosion in one part of the system from causing corrosive action in another part of the system.

As is discussed in Sect. 3.0, internal pipe corrosion is initiated by a reaction between the pipe material and the water it conveys. The corrosion resistance of a pipe material depends on the particular water quality, as well as on the properties of the pipe. For a given water quality, some construction materials may be more corrosion resistant than others. Thus, a finished water may be noncorrosive to one part of a system and corrosive to another.

Table 4.1 lists the most common types of materials found in water supply systems and their uses. Service and home plumbing lines are usually constructed from different materials than transmission or distribution mains. The choice of materials depends on such factors as type of equipment, date equipment was put in service, and cost of materials. Often local building code requirements dictate the use of certain pipe materials.

Table 4.1. Common materials found in water supply systems and their uses

	In-plant systems		Other systems			
Material	Piping	Other	Storage	Transmission and distribution mains	Service lines	Residential and commercial buildings
Wrought iron	X	X		X	X	X
Cast/ductile	X	X		X	X	X
Steel	X	X	X	X	X	X
Galvanized iron	X			X	X	X
Stainless steel		X				X
Copper	X	(brass)			X	X
Lead		X (gaskets)		X	X	X
Asbestos-cement	X			X		
Concrete	X	X	X	X		
Plastic	X	X	X	X	X	X

Source: SUM X, 1981.

Older water systems are more likely to contain cast iron, lead, and vitrified clay pipe distribution lines. The introduction of newer pipe materials, however, has significantly changed pipe-usage trends. For example, ductile iron pipe, introduced in 1948, has completely replaced cast iron pipe, and, currently, all ductile iron pipe is lined with cement or another material, unless specified otherwise. The percentage of A-C pipe use increased from less than 6% to more than 13% between 1960 and 1975. The use of plastic pipe is also increasing, due partly to improvements in the manufacturing of larger-sized pipe and to greater acceptance of plastic pipe in building codes.

Many older systems still have lead service lines operating. Prior to 1960, copper and galvanized iron were the primary service line pipe materials. Although copper and galvanized iron service line pipes are still commonly used, recent trends show an increased use of plastic pipe.

Table 4.2 briefly relates various types of distribution line materials to corrosion resistance and the potential contaminants added to the water. In general, the more inert, nonmetallic pipe materials, such as concrete, A-C, and plastics, are more corrosion resistant.

Table 4.2. Corrosion properties of frequently used materials in water distribution systems

Distribution material	Corrosion resistance	Associated potential contaminants
Copper	Good overall corrosion resistance; subject to corrosive attack from high velocities, soft water, chlorine, dissolved oxygen, and low pH	Copper and possibly iron, zinc, tin, arsenic, cadmium, and lead from associated pipes and solder
Lead	Corrodes in soft water with low pH	Lead (can be well above MCL[a] for lead), arsenic, and cadmium
Mild steel	Subject to uniform corrosion; affected primarily by high dissolved oxygen levels	Iron, resulting in turbidity and red-water complaints
Cast or ductile iron (unlined)	Can be subject to surface erosion by aggressive waters	Iron, resulting in turbidity and red-water complaints
Galvanized iron	Subject to galvanic corrosion of zinc by aggressive waters; corrosion is accelerated by contact with copper materials; corrosion is accelerated at higher temperatures as in hot water systems	Zinc and iron; cadmium and lead (impurities in galvanizing process may exceed primary MCLs)
Asbestos-cement	Good corrosion resistance; immune to electrolysis; aggressive waters can leach calcium from cement	Asbestos fibers
Plastic	Resistant to corrosion	-

[a]MCL = Maximum contaminant levels.

Source: Environmental Science and Engineering, Inc., 1981.

How can the type of materials used throughout a distribution system be identified?

In older and larger systems, identifying the materials of construction may not be an easy task. Researching records, archives, and old blueprints is one approach. Other information sources may be surveys made by local, state, or national organizations, such as local or county health department surveys conducted to identify health-related contaminants in the water as a result of corrosion. The American Water Works Association (AWWA) has conducted several surveys regarding pipe usage. A good source of information about the older parts of the system can be former pipe and equipment installers for the system.

If practicable, utility personnel, such as meter readers or maintenance crews, can determine the type of material used for service and distribution lines, the former by checking the connections at the meter, the latter during routine maintenance checks of the main lines. When sections of pipe are being replaced or repaired, a utility should never pass up the opportunity to obtain samples of the old pipes. An examination of these samples can provide valuable information about the types of materials present in the system and can also aid in determining if the material has been subject to corrosive attack, and if so, to what kind. The sample pipe sections should be tagged and identified by type of material, location of pipe, age of pipe (if known), and date sample was obtained. The type of service (e.g., cold water, hot water, recirculating hot water, apartment, or home) should also be noted.

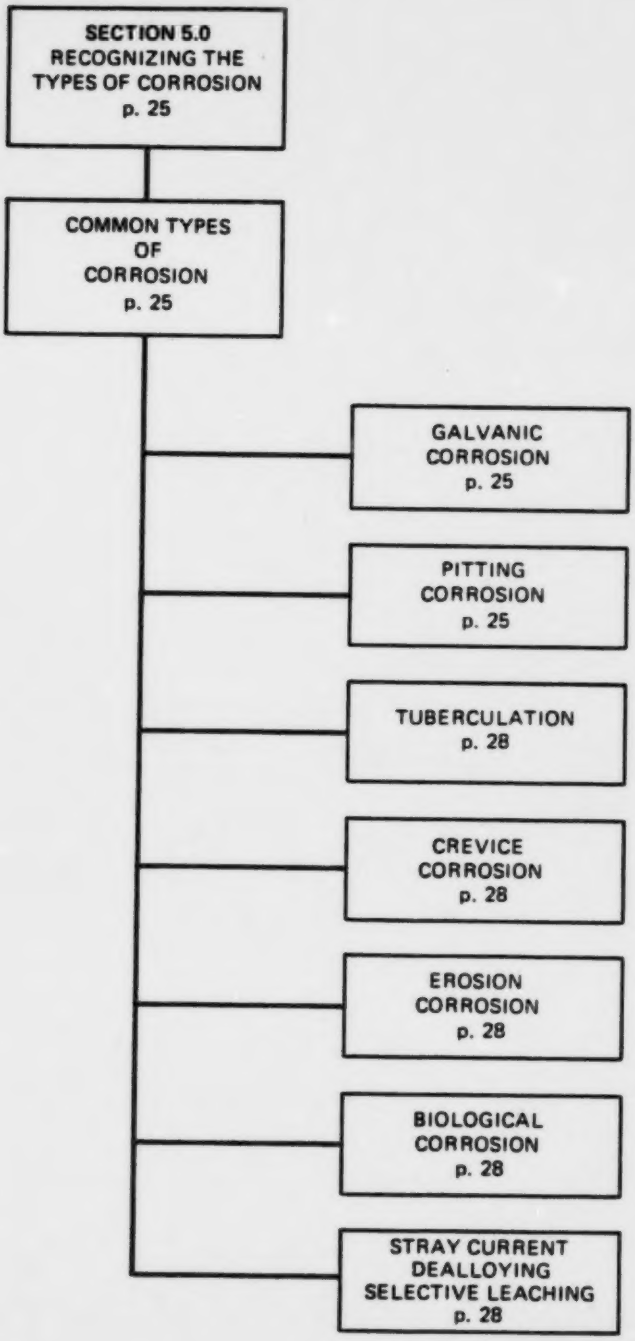
For small utilities with few connections, a house-to-house search to determine the types of materials in the distribution system may be feasible. In smaller communities, water, plumbing, and building contractors in the area could provide useful information about the use and service life of specific materials.

As information is obtained, the utility should keep accurate records which show the type and number of miles of each material used in the system, and its location and use.

A map of the distribution system indicating type, length, and size of pipe materials would be an excellent tool for cataloging this information and could be updated easily when necessary to show additions, alterations, and repairs to the system. As is discussed in Sect. 6.0, the map could also be used in conjunction with other utility records and surveys to identify particular areas and types of materials in the system that are more susceptible to corrosion than others.

ORNL-DWG 83-18347R

INDEX TO SECTION 5


SECTION 5.0
RECOGNIZING THE TYPES OF CORROSION
p. 25
COMMON TYPES OF CORROSION
p. 25
GALVANIC CORROSION
p. 25
PITTING CORROSION
p. 25
TUBERCULATION
p. 28
CREVICE CORROSION
p. 28
EROSION CORROSION
p. 28
BIOLOGICAL CORROSION
p. 28
STRAY CURRENT
DEALLOYING
SELECTIVE LEACHING
p. 28

5.0 RECOGNIZING THE TYPES OF CORROSION

Previous sections have included discussions of the symptoms, basic characteristics, and chemical reactions of corrosion. The following questions will now be addressed.

How many types of corrosion are there? How can utility personnel recognize which type of corrosion is occurring in the system?

Literally dozens of types of corrosion exist. This section identifies the types of corrosion most commonly found in the waterworks industry and describes the basic characteristics of each. Illustrations are presented to help the reader identify each type by appearance. Recognizing the different types of corrosion often helps to identify their causes. Once the cause of the corrosion is diagnosed, it is easier to prescribe appropriate preventative or control measures to reduce the corrosive action.

Corrosion can be either uniform or nonuniform. Uniform corrosion results in an equal amount of material being lost over an entire pipe surface. Except in extreme cases, the loss is so minor that the service life of the pipe is not adversely affected. Nonuniform corrosion, on the other hand, attacks smaller, localized areas of the pipe causing holes, restricted flow, or structural failures. As a result, the piping will fail and will have to be replaced much sooner.

The most common types of corrosion in the waterworks industry are (1) galvanic corrosion, (2) pitting, (3) crevice corrosion, (4) erosion corrosion, and (5) biological corrosion.

Galvanic corrosion (as discussed in Sect. 3.0) is corrosion caused by two different metals or alloys coming in contact with each other. This usually occurs as joints and connections. Due to the differences in their activity, the more active metal corrodes. Galvanic corrosion is common in household plumbing systems where different types of metals are joined, such as a copper pipe to a galvanized iron pipe. Service line pipes are often of a different metal than household lines, so the point at which the two are joined is a prime target for galvanic corrosion. Galvanic corrosion is especially severe when pipes of different metals are joined at elbows, as is illustrated in Fig. 5.1.

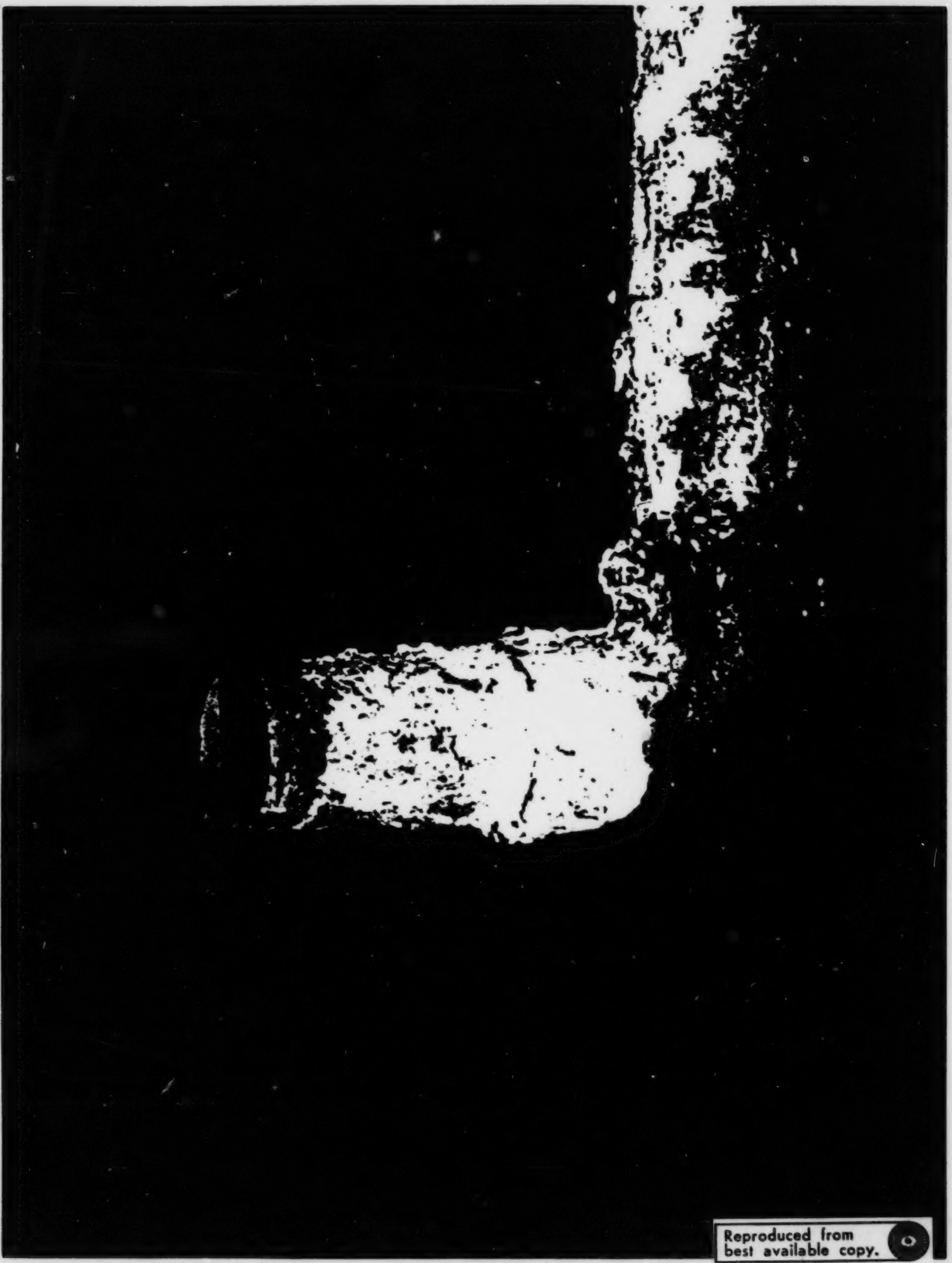
This type of corrosion should be expected when different metals are used in the same system. It is common to use brass valves in galvanized lines or to use galvanized fittings in copper lines, especially at hot water heaters. An example is shown in Fig. 5.2, where a brass valve has been used in a galvanized line. Galvanic corrosion usually results in a localized attack and deep pitting. Often the threads of the pipe are the point of attack and show many holes all the way through the pipe wall. The outside of the pipe may show strong evidence of corrosion because some of the corrosion products will leak through and dry on the outside surface. Galvanic corrosion is particularly bad when a small part of the system is made up of the more active metal, such as a galvanized nipple in a copper line. In such cases, the galvanized nipple provides a small anode area which corrodes, and the copper lines provide a large cathode area to complete the reaction. Therefore, it is important to minimize the size of the cathode. Oxygen can also play a part in galvanic corrosion, as is discussed in Sect. 3.0.

Galvanic corrosion can be reduced by avoiding dissimilar metal connections or by using dielectric couplings to join the metals when this is not possible. Because galvanic corrosion is caused by the difference in activity or potential between two metals, the closer two metals are to each other in the galvanic series (Table 3.1), the less the chance for galvanic corrosion to occur. For this reason, a brass-to-copper connection is preferable to a zinc-to-copper connection.

Pitting is a damaging, localized, nonuniform corrosion that forms pits or holes in the pipe surface. It actually takes little metal loss to cause a hole in a pipe wall, and failure can be rapid. Pitting can begin or concentrate at a point of surface imperfections, scratches, or surface deposits. Frequently, pitting is caused by ions of a metal higher in the galvanic series plating out on the pipe surface. For example, steel and galvanized steel are subject to corrosion by small quantities (about 0.01 mg/L) of soluble metals, such as copper, which plate out and cause a galvanic type of corrosion. Chloride ions in the water commonly accelerate pitting. The presence of DO and/or high chlorine residuals (>0.4 mg/L) in water may cause pitting corrosion of copper.

25.a

Top — Crop As Marked



Reproduced from
best available copy.

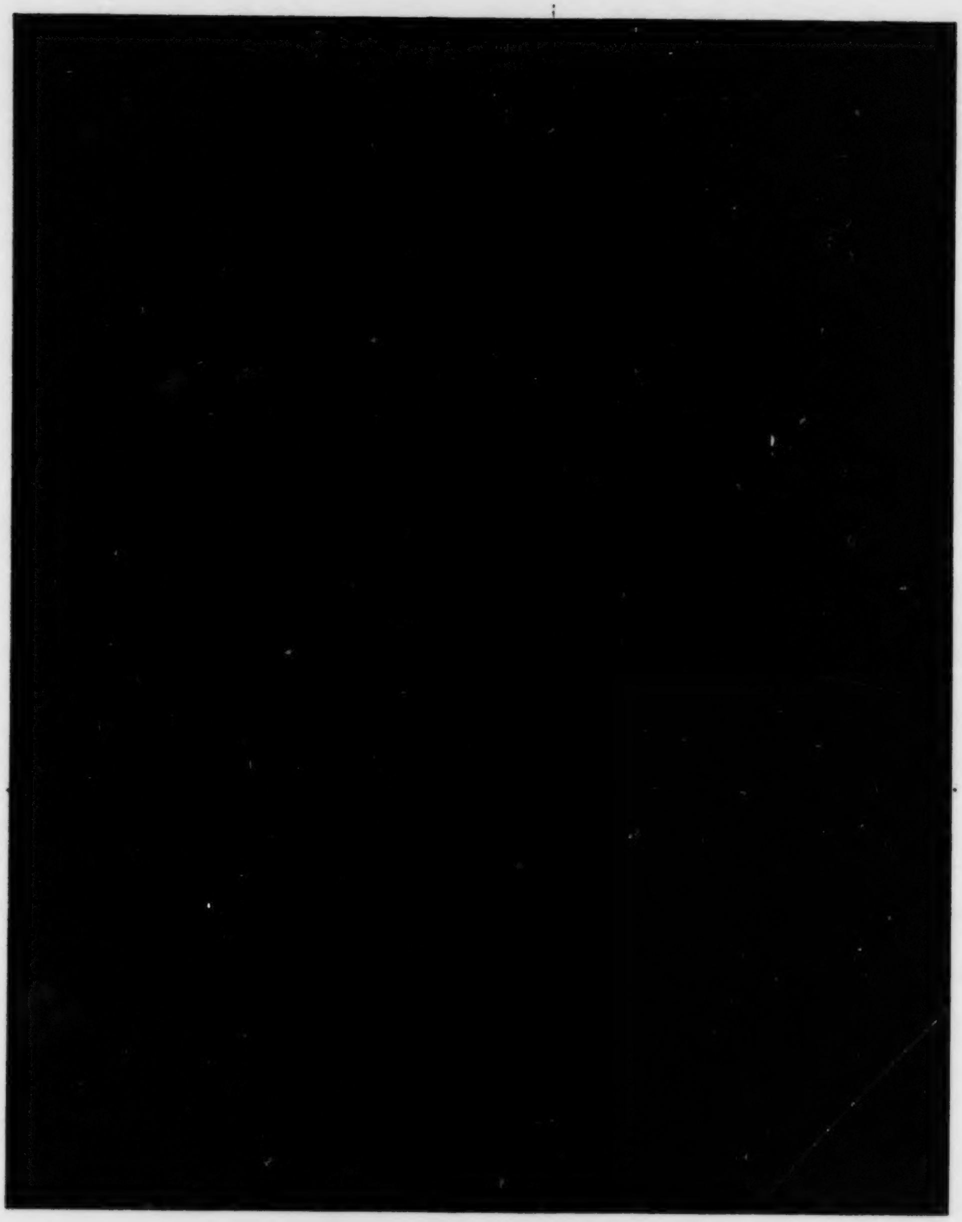


Fig. 5.1. Galvanic corrosion resulting from a galvanized pipe joined to a copper pipe by a brass elbow.

Top -

26.a

Reproduced from
best available copy.

Fig. 5.2. Galvanic corrosion illustrated by severely corroded galvanized steel nipple in a brass elbow. *This was the only piece of steel pipe in an otherwise all brass domestic hot-water heater, illustrating the effects of a large cathodic area to a small anodic area.*

Pitting is not usually noticed until the pipe wall gets a hole in it and the effect of the corrosion becomes obvious, as does the location of the pit. This type of corrosion also occurs in storage tanks at the water line, where the air and water come in contact and create corrosive conditions. Examples of pitting corrosion are shown in Figs. 5.3 and 5.4.

Tuberculation occurs when pitting corrosion products build up at the anode next to the pit, as illustrated in Fig. 5.5. In iron or steel pipes, the tubercles are made up of rust or iron oxide. These tubercles are usually rust colored and soft on the outside and are both harder and darker toward the inside. When copper pipe becomes pitted, the tubercle buildup is smaller and is a green to blue-green color. Examples of tuberculation are illustrated in Figs. 5.6 and 5.7.

Tuberculation is seen only when a piece of pipe is removed from the system because it rarely affects the water quality, although it is possible for some of the tubercles to break loose with changes in flow or when the pipes are hit hard enough to loosen them. This type of corrosion can be suspected, though, when the flow through a pipe is much less than should be expected, as tubercles add to the roughness of a main's interior and reduce the flow. In extreme cases, the flow can be completely stopped by tubercles.

Crevice corrosion is a form of localized corrosion usually caused by changes in acidity, oxygen depletion, dissolved ions, and the absence of an inhibitor. As the name implies, this corrosion occurs in crevices at gaskets, lap joints, rivets, and surface deposits.

Erosion corrosion mechanically removes protective films, such as metal oxides and $CaCO_3$, which serve as protective barriers against corrosive attack. It generally results from high flow velocities, turbulence, sudden changes in flow direction, and the abrasive action of suspended materials. Erosion is much worse at sharp bends, as is illustrated in Fig. 5.8. Erosion corrosion can be identified by grooves, waves, rounded holes, and valleys it causes on the pipe walls. **Cavitation corrosion** is a type of erosion corrosion and is caused by the presence of bubbles which destroy any protective film. Cavitation occurs mainly in or near pumps. An example is shown in Fig. 5.9.

Biological corrosion results from a reaction between the pipe material and organisms such as bacteria, algae, and fungi. It is an important factor in the taste and odor problems that develop in a system, as well as in the degradation of the piping materials. Controlling such growths is complicated because they can take refuge in many protected areas, such as in mechanical crevices or in accumulations of corrosion products. The bacteria can exist under tubercles, where neither chlorine nor oxygen can destroy them. Mechanical cleaning may be necessary in some systems before control can be accomplished by residual disinfectants. Preventative methods include avoiding dead ends and stagnant water in the system.

Other types of corrosion in the waterworks industry that are not found as commonly as those discussed previously include (1) stray current corrosion and (2) dealloying or selective leaching.

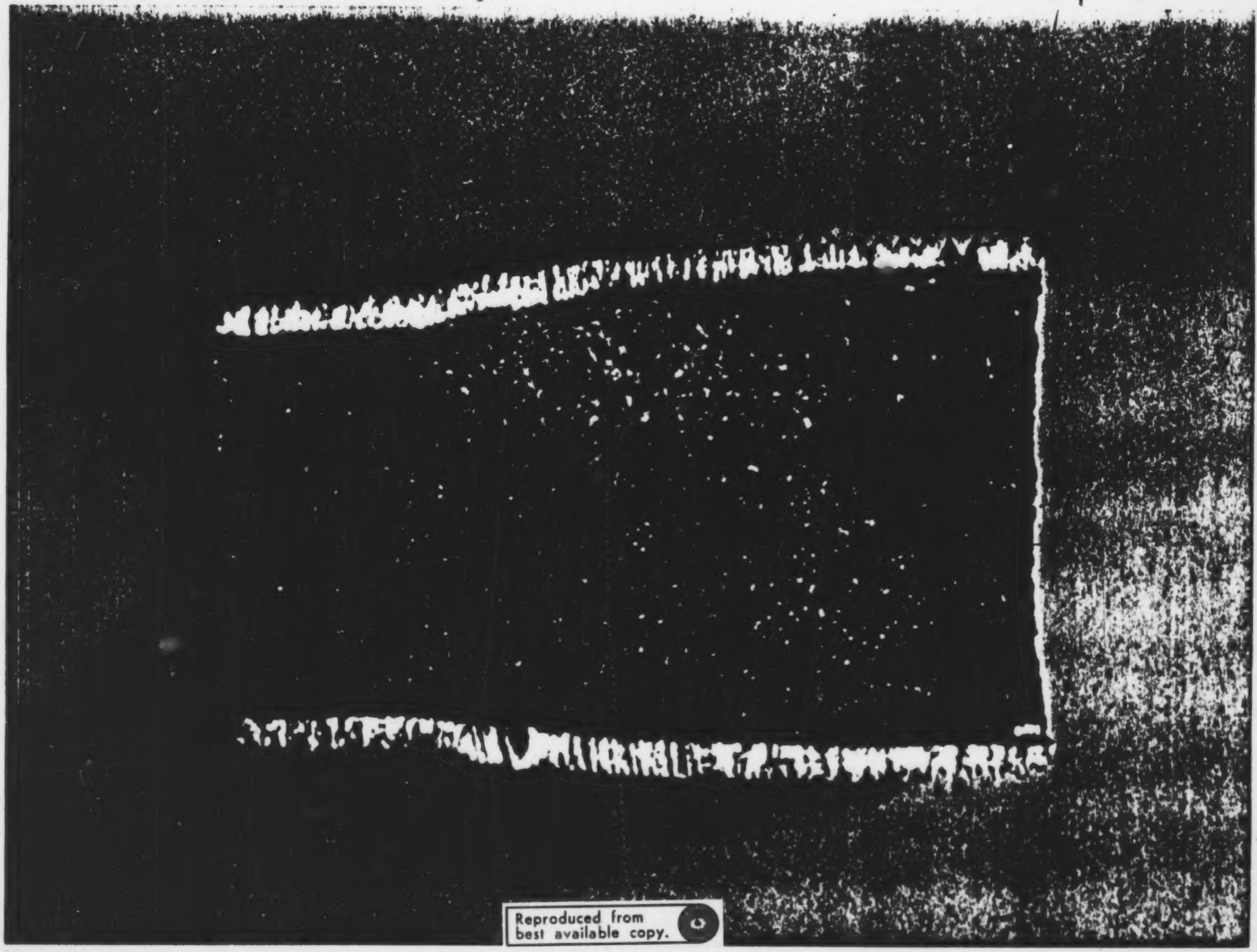
Stray current corrosion is a type of localized corrosion usually caused by the grounding of home appliances or electrical circuits to the water pipes. Corrosion takes place at the anode, the point where the current leaves the metal to return to the power source or to ground. Stray current corrosion is difficult to diagnose since the point of corrosion does not necessarily occur near the current source. It occurs more often on the outside of pipes, but does show up in house faucets or other valves. Fig. 5.10 is an example of stray current corrosion.

Dealloying or selective leaching is the preferential removal of one or more metals from an alloy in a corrosive medium, such as the removal of zinc from brass (dezincification). This type of corrosion weakens the metals and can lead to pipe failure in severe cases. Dezincification is common in brasses containing 20% or more zinc and is rare in brasses containing less than 15% zinc. An example of this is shown in Fig. 5.11.

Crop As Marked

top—

28.a



Reproduced from best available copy.

Fig. 5.3. Pitting of steel pipe.

Crop as marked -top-

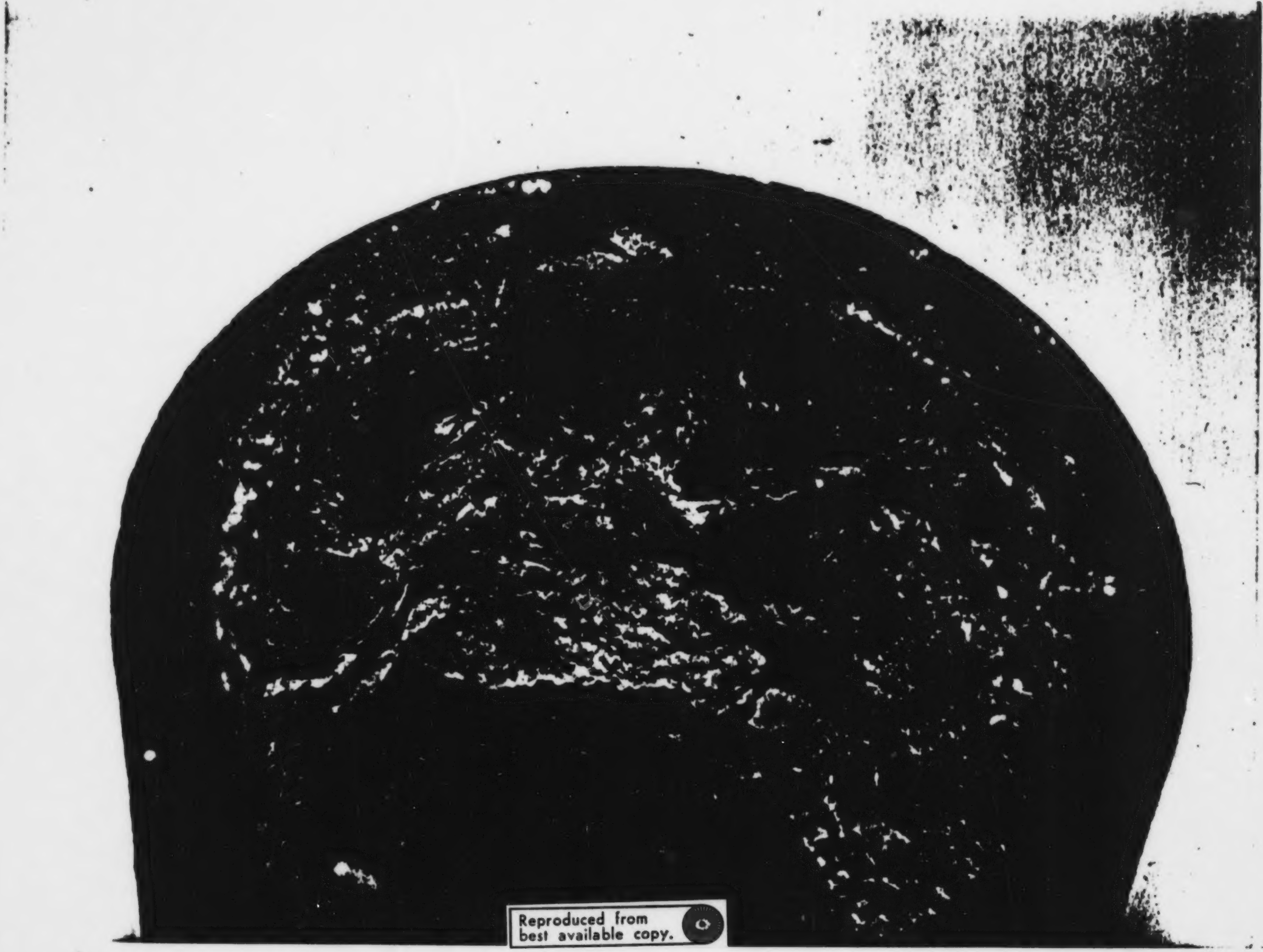
29.a

B 369

Reproduced from
best available copy.

Fig. 5.4. Pitted red brass (85% copper) pipe from a domestic hot-water system.

Crop as Marked

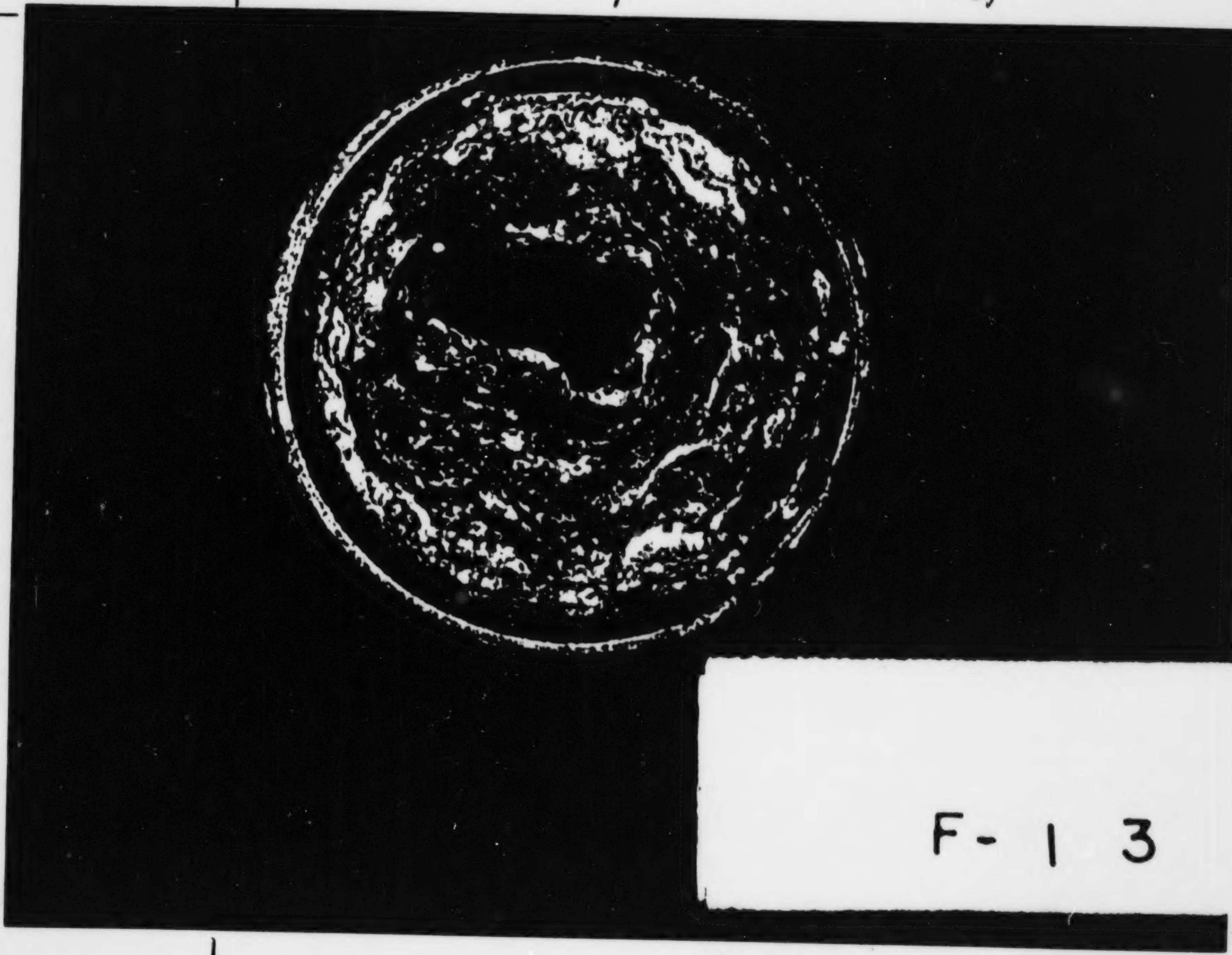


30.a

Reproduced from
best available copy.

Fig. 5.5. Tuberculation in a cast iron pipe.

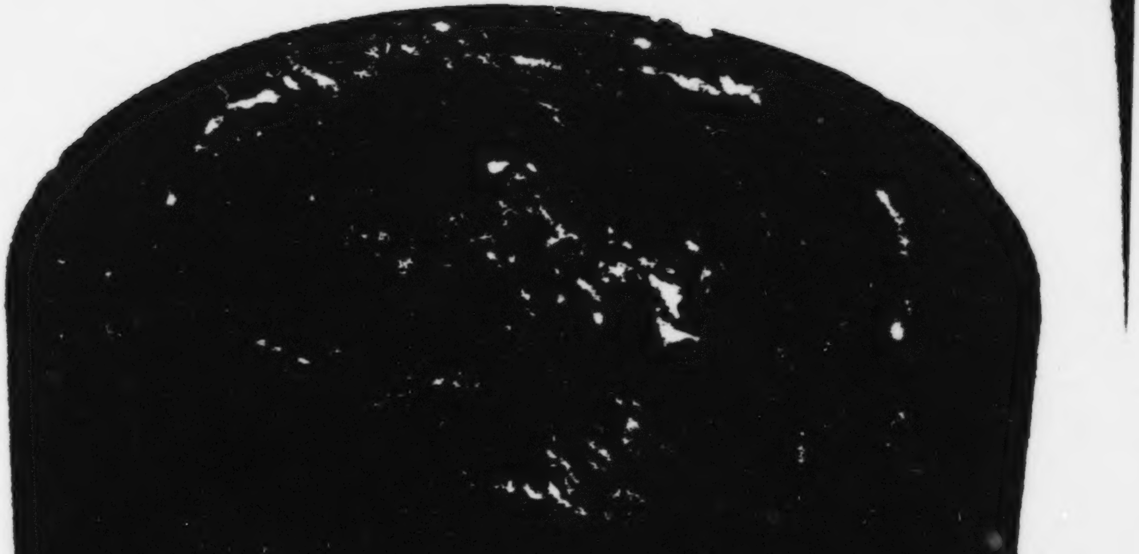
Crop to Marked -10,[illegible]-



F-13

Fig. 5.6. Galvanized steel pipe from a domestic hot-water system showing almost complete clogging by corrosion products.

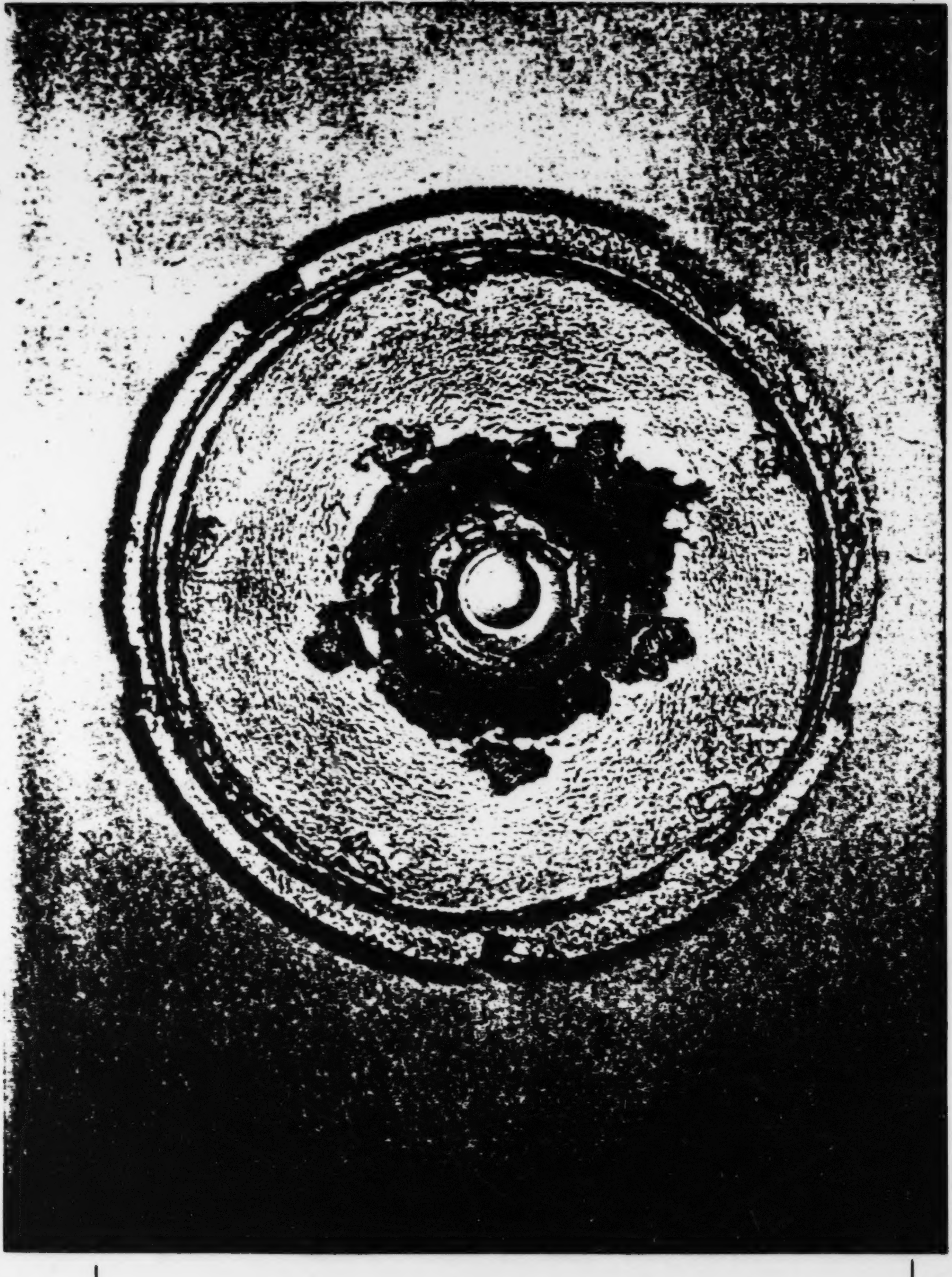
Crop As Marked -1 of- 33.a



F
S

Fig. 5.7. Tuberculation in a cast iron pipe.

33.a



Crop As Marked

1μ

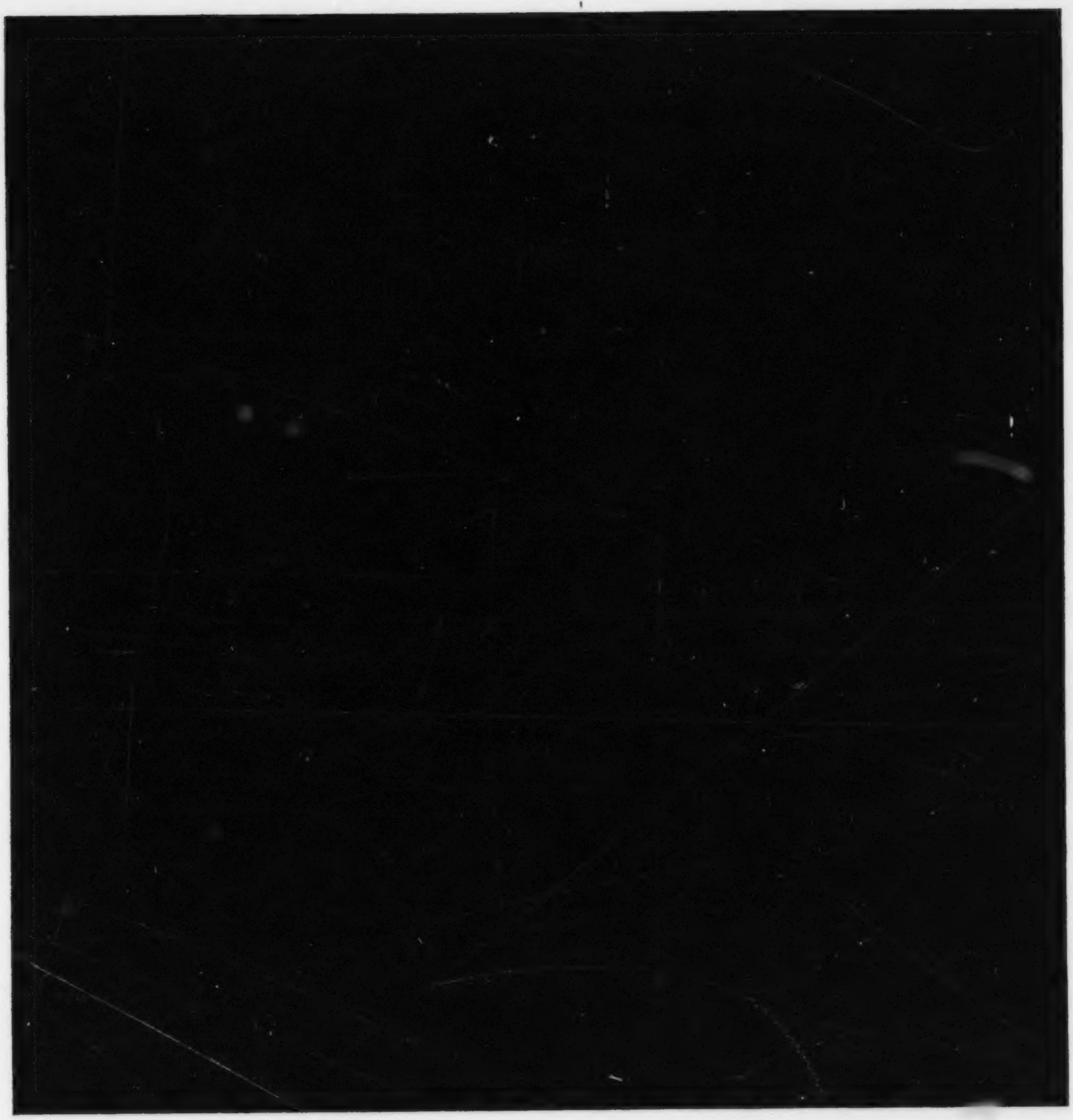


Fig. 5.8. Erosion corrosion of yellow brass impeller from domestic hot-water circulation pump.

34.a

-Top- Crop As Marked

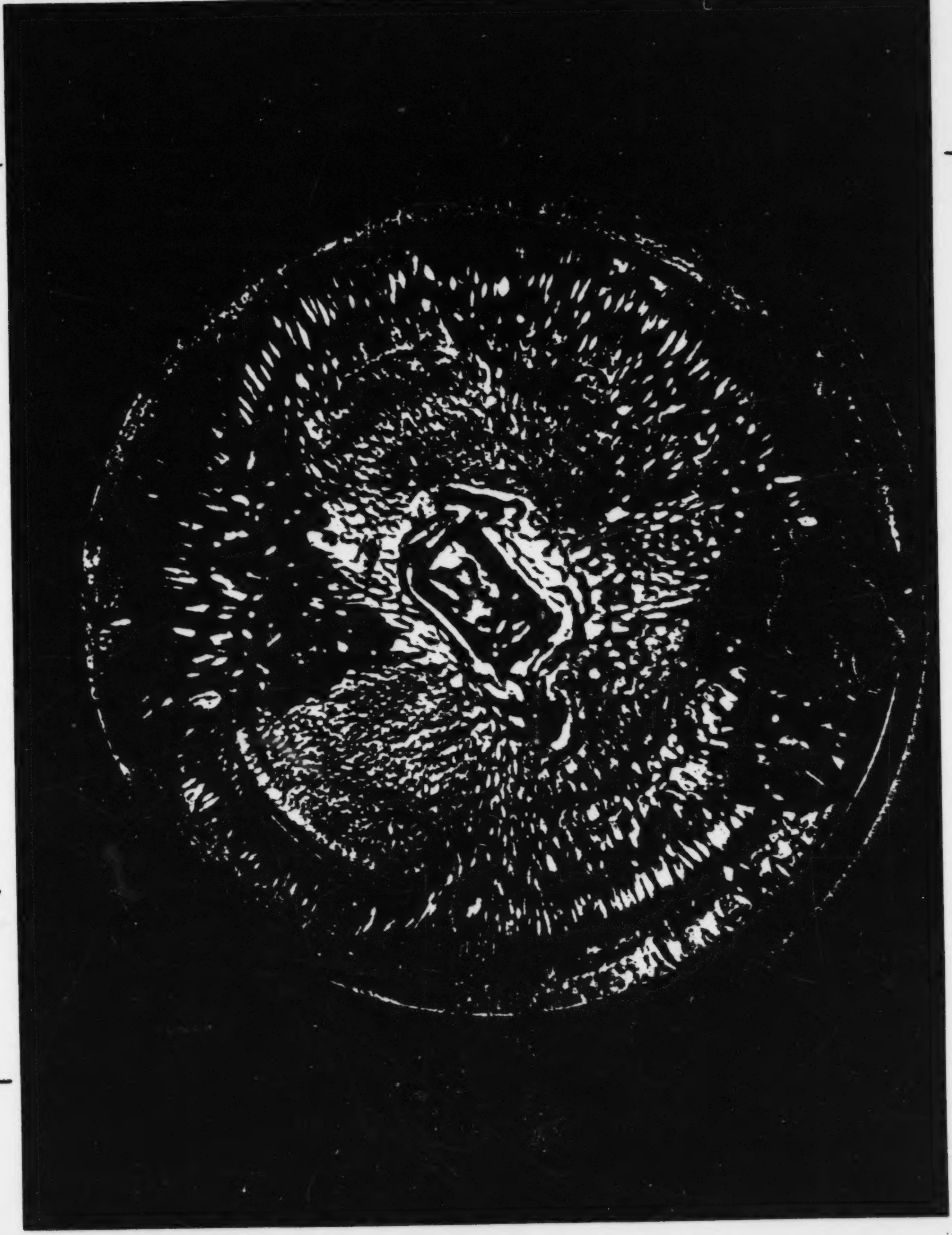
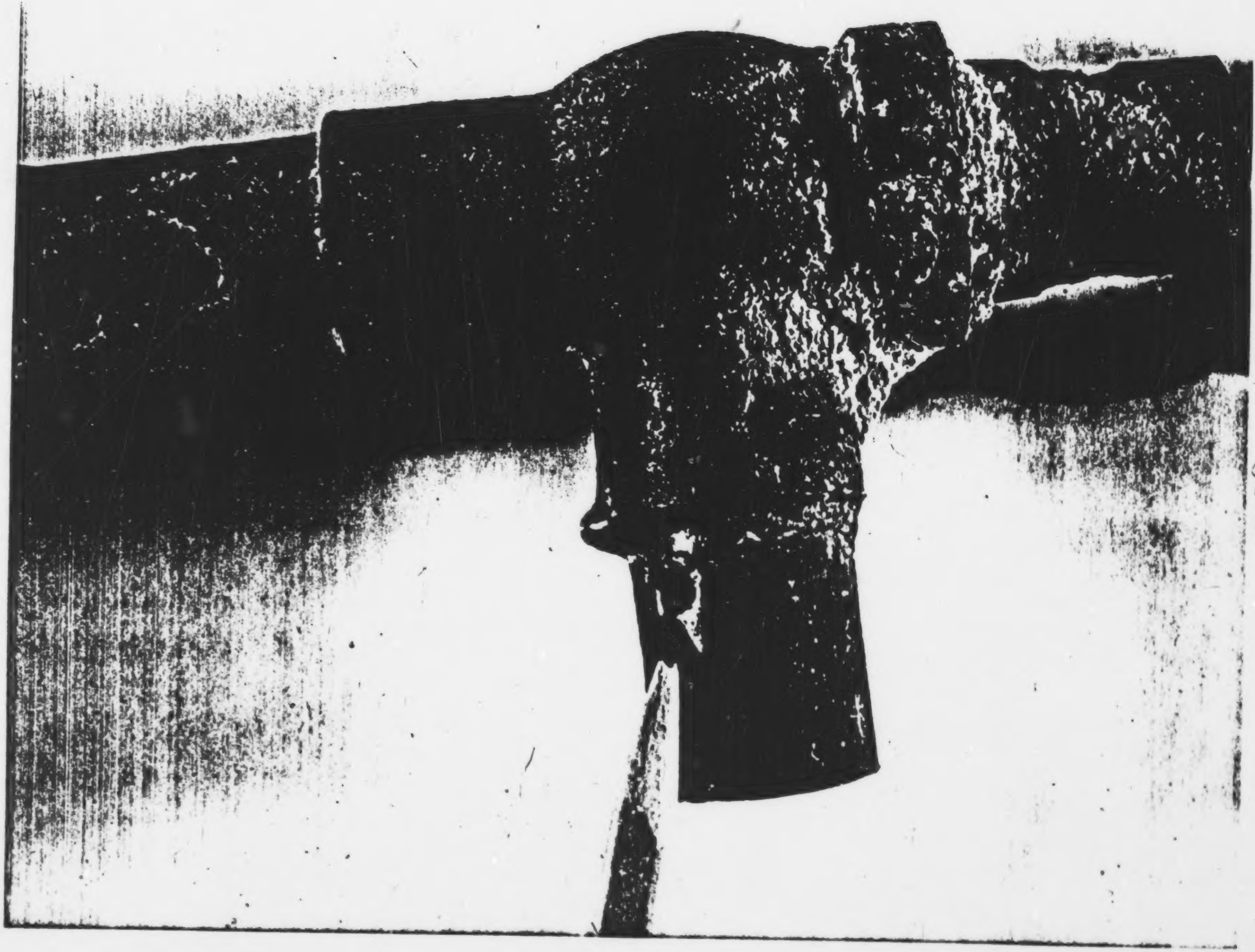


Fig. 5.9. Cavitation corrosion of brass impeller.

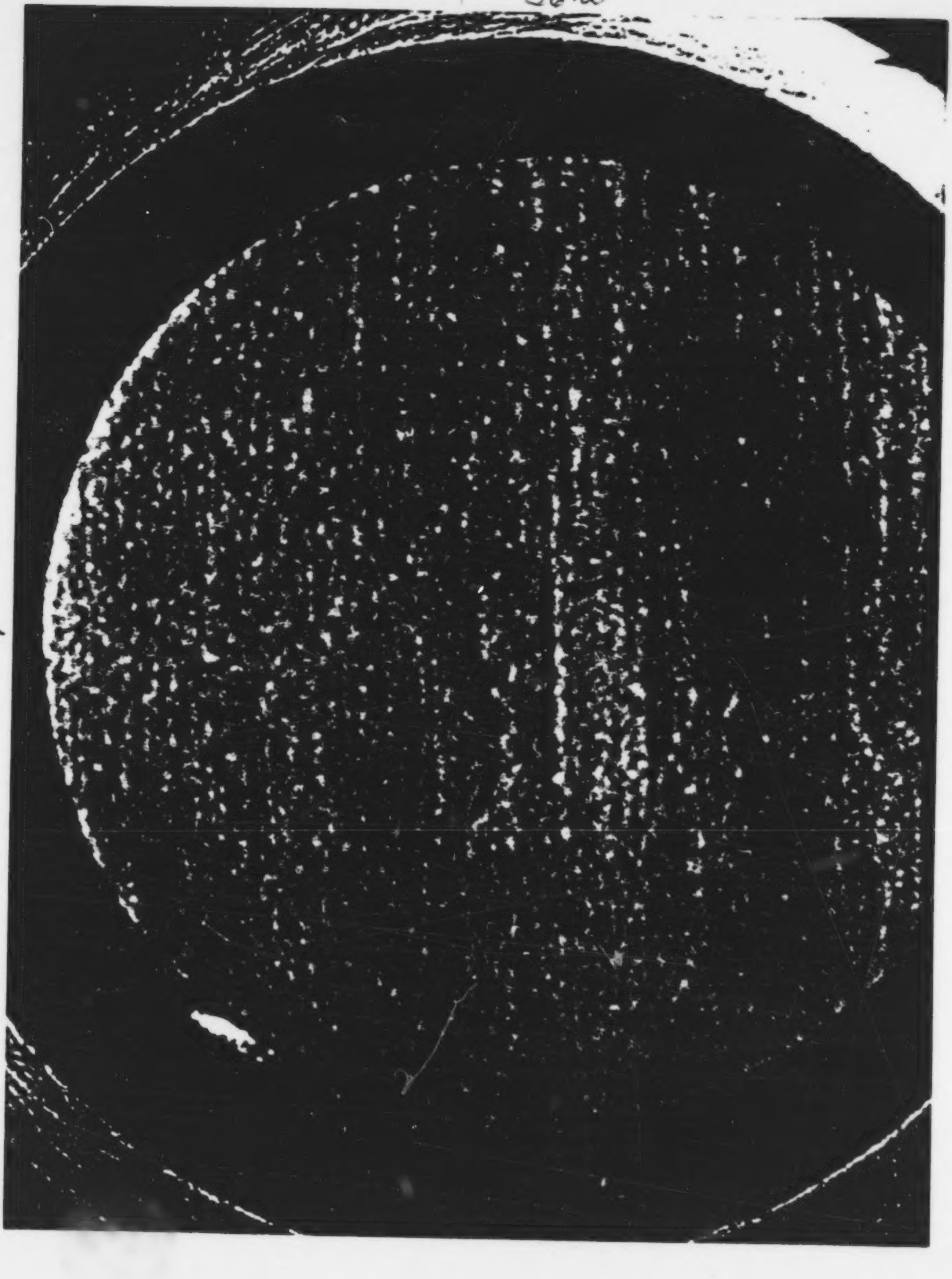
Top



35.a

Fig. 5.10. Extreme example of stray current corrosion in an outside water faucet caused by lightning leaving the pipe.

36.a



— 1μ —

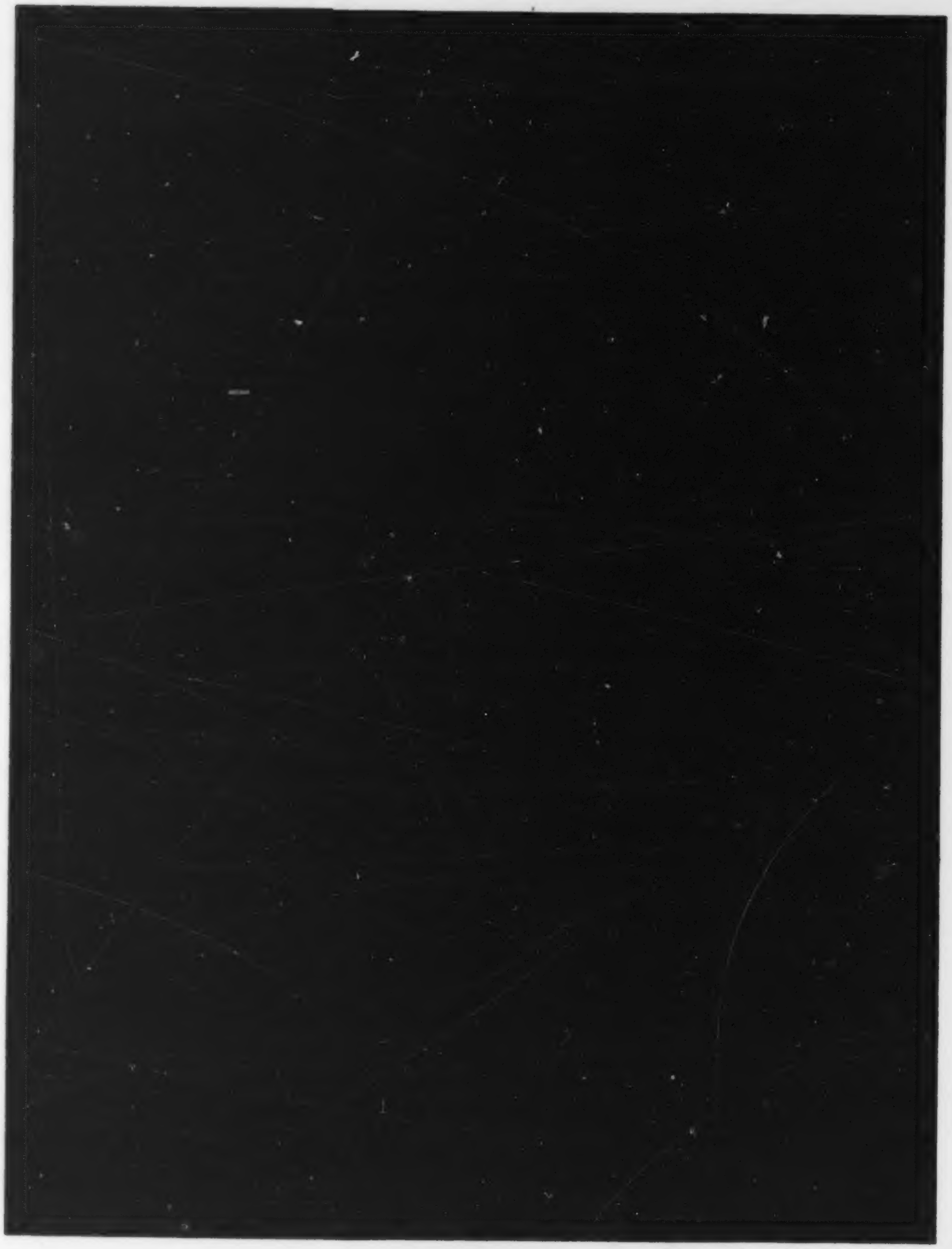
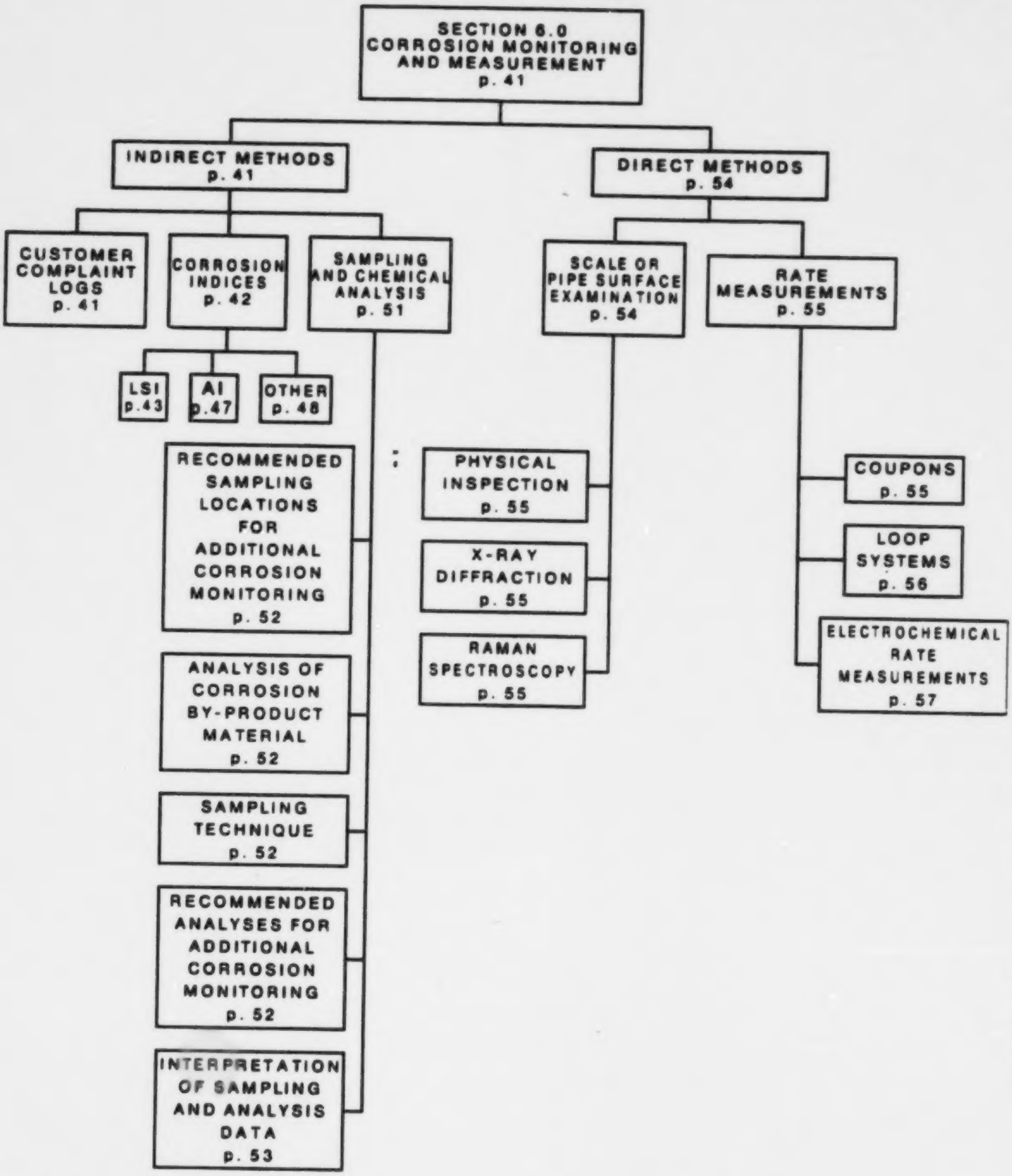


Fig. 5.11. Dezincification of yellow brass in domestic water pipe.

INDEX TO SECTION 6

ORNL-DWG 83C-18348


SECTION 6.0 CORROSION MONITORING AND MEASUREMENT p. 41
INDIRECT METHODS p. 41
DIRECT METHODS p. 54
CUSTOMER COMPLAINT LOGS p. 41
CORROSION INDICES p. 42
SAMPLING AND CHEMICAL ANALYSIS p. 51
SCALE OR PIPE SURFACE EXAMINATION p. 54
RATE MEASUREMENTS p. 55
LSI p.43
AI p.47
OTHER p. 48
RECOMMENDED SAMPLING LOCATIONS FOR ADDITIONAL CORROSION MONITORING p. 52
ANALYSIS OF CORROSION BY-PRODUCT MATERIAL p. 52
SAMPLING TECHNIQUE p. 52
RECOMMENDED ANALYSES FOR ADDITIONAL CORROSION MONITORING p. 52
INTERPRETATION OF SAMPLING AND ANALYSIS DATA p. 53
PHYSICAL INSPECTION p. 55
X-RAY DIFFRACTION p. 55
RAMAN SPECTROSCOPY p. 55
COUPONS p. 55
LOOP SYSTEMS p. 56
ELECTROCHEMICAL RATE MEASUREMENTS p. 57

Preceding page blank

6.0 CORROSION MONITORING AND MEASUREMENT

The previous sections of this manual have discussed what corrosion is and have briefly described how and why corrosion occurs in the waterworks industry. The purpose of this and the following sections is to point out some of the easiest, as well as the most effective, methods of identifying, monitoring, and correcting corrosion-related problems. In other words, these sections answer the questions how do you know if your utility has a corrosion problem, and what can you do to control or reduce the affects of the corrosion. The effects of corrosion, which may not be evident without monitoring, can be expensive and may even affect human health. Monitoring methods most useful to the small water utility are emphasized; that is, those methods which are the least expensive and the simplest to implement in terms of manpower and technical requirements. Methods for controlling or reducing corrosion are covered in the following section.

Just as there is no one cause of corrosion, there is no one way to measure or "cure" corrosion. Since corrosion in a system depends on a specific water and the reaction of that water with specific pipe materials, each utility is faced with a unique set of problems. There are, however, general methods of measuring and monitoring for corrosion that can provide a basis for a sound corrosion control program for any utility. Although no one method may provide an absolute or quantitative measure of corrosivity, several methods used together over a period of time will indicate if corrosion is occurring and will point out any undesirable effects on the system.

There are two different kinds of corrosion measurements—indirect and direct. The indirect methods do not measure corrosion rates. Rather, the data obtained from these methods must be compared and interpreted to determine trends or changes in the system. The indirect methods discussed here are (1) customer complaint logs, (2) corrosion indices, and (3) water sampling and chemical analyses. The direct corrosion measurements call for the actual examination of a corroded surface or the measurement of corrosion rates, particularly actual metal loss. The direct methods discussed here are (1) examination of pipe sections and (2) rate measurements.

6.1 INDIRECT METHODS

Customer Complaint Logs

Usually, customer complaints will be the first evidence of a corrosion problem in a water system. The most common symptoms are listed in Table 6.1, along with their possible causes. The

Table 6.1. Typical customer complaints due to corrosion

Customer complaint	Possible cause
Red water or reddish-brown staining of fixtures and laundry	Corrosion of iron pipes or presence of iron in raw water
Bluish stains on fixtures	Corrosion of copper lines
Black water	Sulfide corrosion of copper or iron lines
Foul taste and/or odors	By-products from microbial activity
Loss of pressure	Excessive scaling, tubercle build-up from pitting corrosion, leak in system from pitting or other type of corrosion
Lack of hot water	Build-up of mineral deposits in hot water system (can be reduced by setting thermostat to under 140°F)
Short service life of household plumbing	Rapid deterioration of pipes from pitting or other types of corrosion

Source: Environmental Science and Engineering, Inc., 1982.

Preceding page blank

complaints may not always be due to corrosion. For example, red water may also be caused by iron in the raw water that is not removed in treatment. Therefore, in some cases, further investigation is necessary before attributing the complaint to corrosion in the system.

Complaints can be a valuable corrosion monitoring tool if records of the complaints are organized. The complaint record should include the customer's name and address, date the complaint was made, and nature of the complaint. The following information should also be recorded:

1. Type of material (copper, galvanized iron, plastic, etc.) used in the customer's system;
2. Whether the customer uses home treatment devices prior to consumption (softening, carbon filters, etc.);
3. Whether the complaint is related to the hot water system and, if so, what type of material is used in the hot water tank and its associated appurtenances; and
4. Any follow-up action taken by the utility or customer.

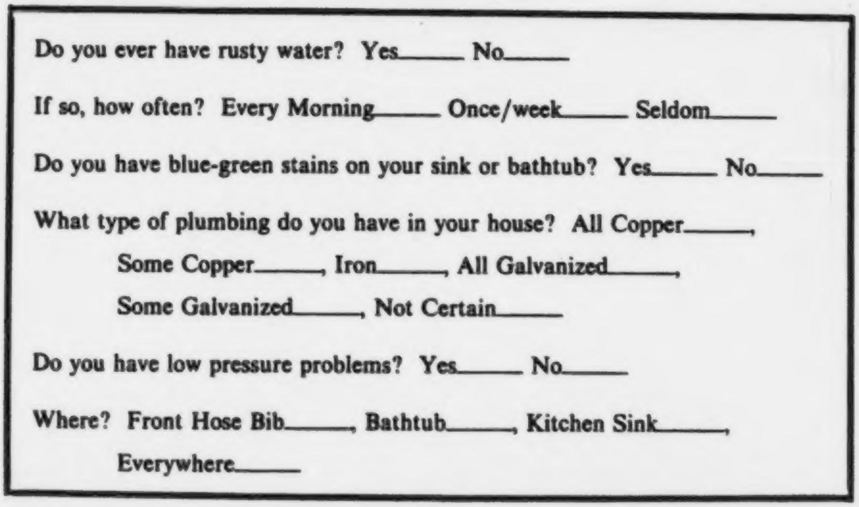
These records can be used to monitor changes in water quality due to system or treatment changes.

The development of a complaint map is useful in pinpointing problem areas. The complaint map would be most useful when combined with the materials map discussed in Sect. 4.0, which indicates the location, type, age, and use of a particular type of construction material. If complaints are recorded on the same map, the utility can determine if there is a relationship between complaints and the materials used. To supplement the customer complaint records, it might be useful to send questionnaires to a random sampling of customers. These questionnaires should be short but thorough. A sample questionnaire used by the city of Seattle is shown in Fig. 6.1.

Customer complaint records and questionnaires are useful monitoring tools that can be used as part of any corrosion monitoring and control program. The low costs associated with keeping a good record of complaints can be well worth the time. The resulting information would indicate the real effect of water quality at the customer's tap and would show the effect of any process changes made as part of a corrosion control program.

Corrosion Indices

Many attempts have been made to develop an index that would predict whether or not a water is corrosive; unfortunately, none of these attempts has been entirely successful. However, several of



Do you ever have rusty water? Yes_____ No_____

If so, how often? Every Morning_____ Once/week_____ Seldom_____

Do you have blue-green stains on your sink or bathtub? Yes_____ No_____

What type of plumbing do you have in your house? All Copper_____,
Some Copper_____, Iron_____, All Galvanized_____,
Some Galvanized_____, Not Certain_____

Do you have low pressure problems? Yes_____ No_____

Where? Front Hose Bib_____, Bathtub_____, Kitchen Sink_____,
Everywhere_____

Fig. 6.1. Sample questionnaire. Source: City of Seattle, 1981.

the indices can be useful for predicting corrosion. These indices can be calculated by all small utilities and can be used in an overall corrosion control program. In addition, the 1980 amendments to the NIPDWR require all community water supply systems to determine either the Langelier Saturation Index (LSI) or the Aggressive Index (AI) and report these values to the state regulatory agencies.

Since the LSI and AI are the two most commonly used corrosion indices in the waterworks industry, they are the only indices discussed in detail in the following paragraphs. However, several of the less frequently used indices are briefly described to acquaint the reader with their usefulness and method of calculation.

The LSI and the AI indices estimate the tendency of a water to "lay down" or precipitate a protective coating of $CaCO_3$ on the pipe wall. A thin layer of $CaCO_3$ is desirable, as it keeps the water from contacting the pipe and reduces the chance of corrosion.

"Scaling" occurs when thick layers of $CaCO_3$ are deposited. Although the pipe is protected from corrosion, excessive scaling can result in loss of carrying capacity in the system, as is shown in Fig. 6.2.

The equation for the deposition of $CaCO_3$ scale is

$$\underset{\text{Calcium}}{Ca^{++}} + \underset{\text{Bicarbonate}}{HCO_3^-} \rightleftharpoons \underset{\text{Calcium carbonate}}{CaCO_3} + \underset{\text{Hydrogen Ion}}{H^3} \qquad (9)$$

If the reaction proceeds to the right, a protective scale of $CaCO_3$ is deposited. If the reaction proceeds to the left, the scale is dissolved, leaving the surfaces that had been protected exposed to corrosion. When the water is exactly saturated with $CaCO_3$, it will neither dissolve nor deposit $CaCO_3$. The saturation value of the water with respect to $CaCO_3$ depends on the calcium ion concentration, alkalinity, temperature, pH, and the presence of other dissolved materials, such as chlorides and sulfates.

Langelier Saturation Index. The LSI is the most widely used and misused index in the water treatment and distribution field. The index is based on the effect of pH on the solubility of $CaCO_3$. The pH at which a water is saturated with $CaCO_3$ is known as the pH of saturation or pH_s. At pH_s, a protective scale will neither be deposited nor dissolved. The LSI is defined by the following equation:

$$LSI = pH - pH_s \qquad (10)$$

The results of the equation are interpreted as follows:

$LSI > 0$ Water is supersaturated and tends to precipitate a scale layer of $CaCO_3$.

$LSI = 0$ Water is saturated (in equilibrium) with $CaCO_3$; a scale layer of $CaCO_3$ is neither precipitated nor dissolved.

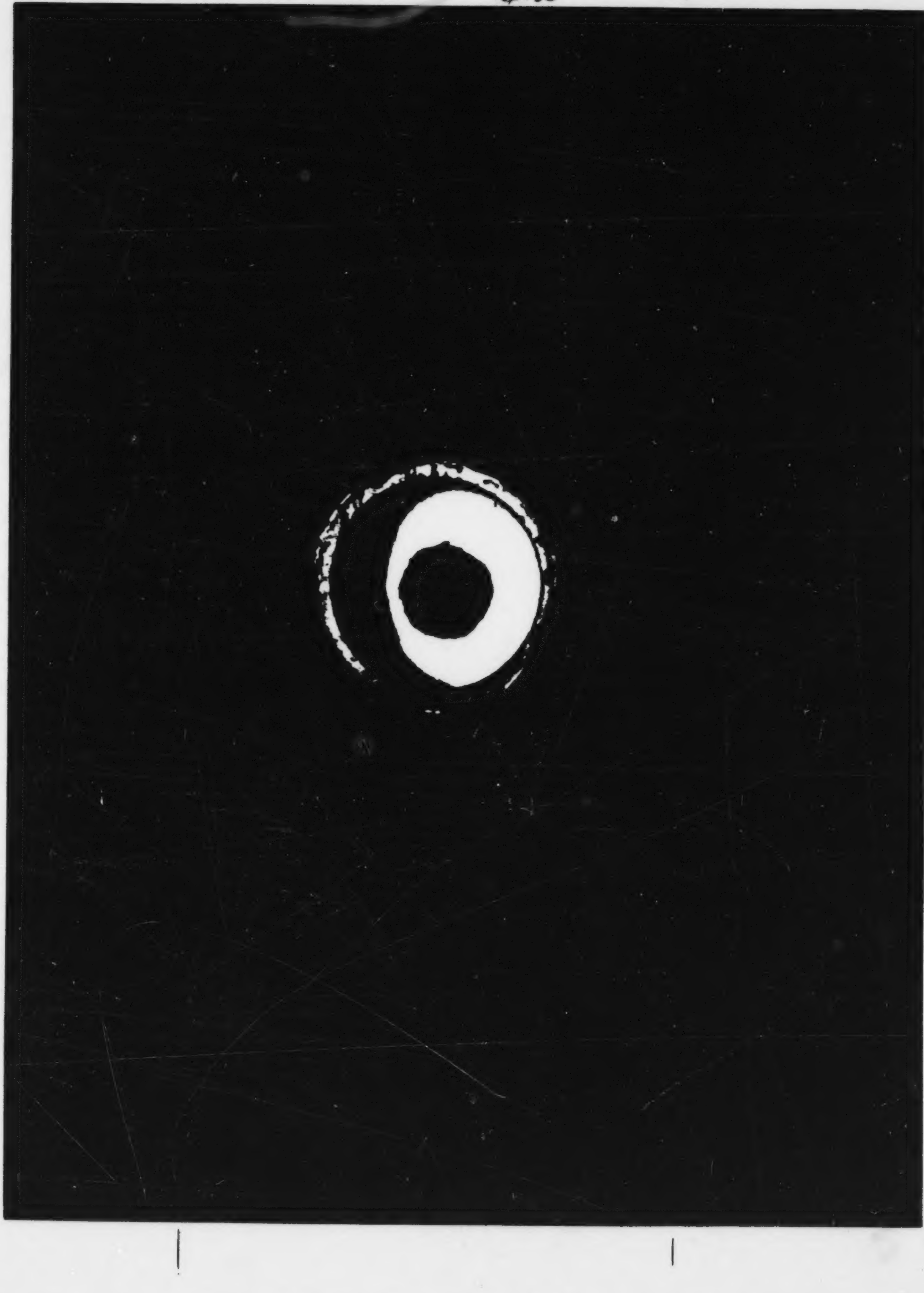
$LSI < 0$ Water is undersaturated, tends to dissolve solid $CaCO_3$.

To calculate the LSI, the following information is needed:

1. Total alkalinity (milligrams per liter) as $CaCO_3$;
2. Calcium, mg/L, as $CaCO_3$;
3. Total dissolved solids, mg/L;
4. pH;
5. Temperature; and
6. pH_s.

The value of pH_s can be calculated by the following equation:

43.a



Crop As Marked -10%-

Crop As Marked -top-

43.6

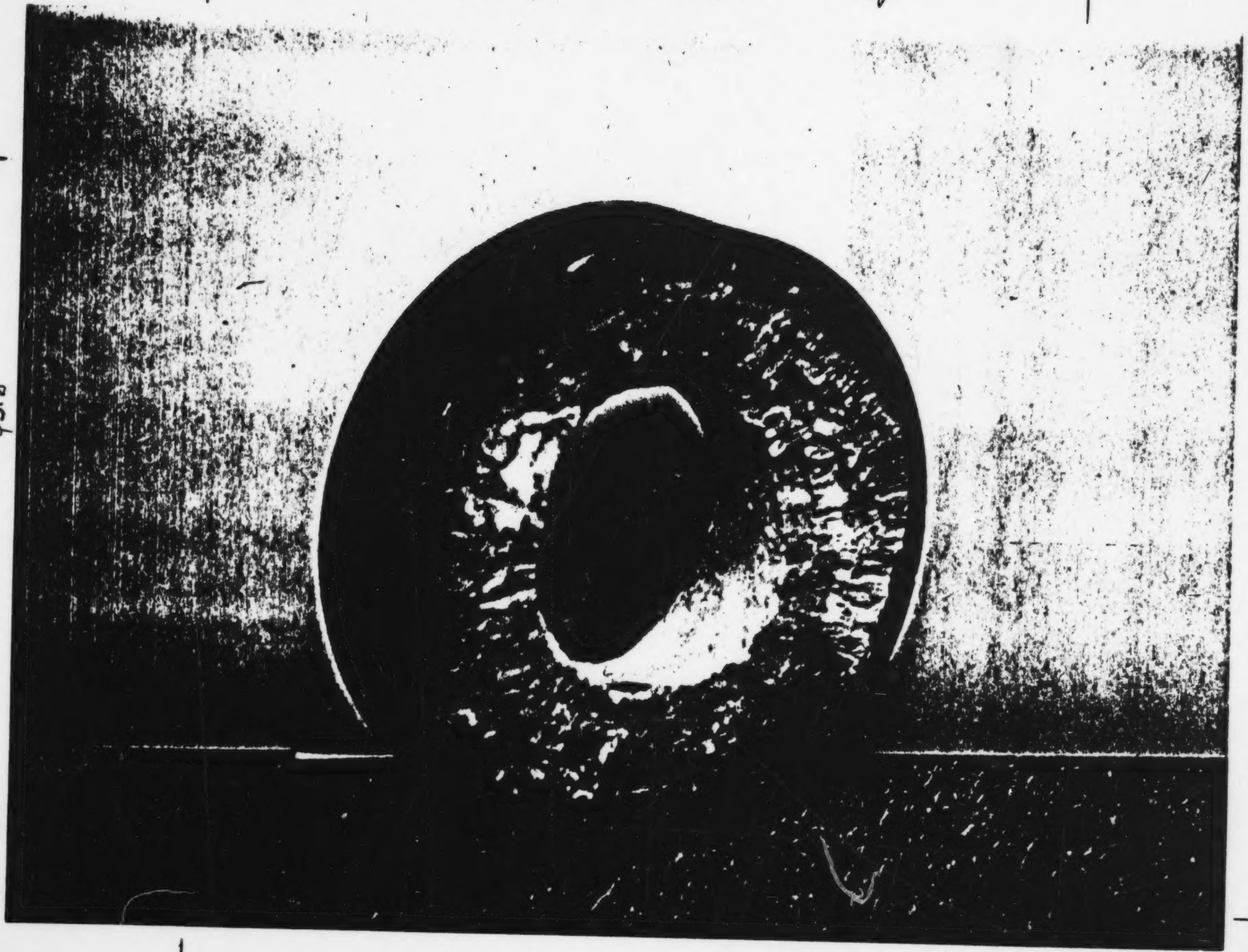
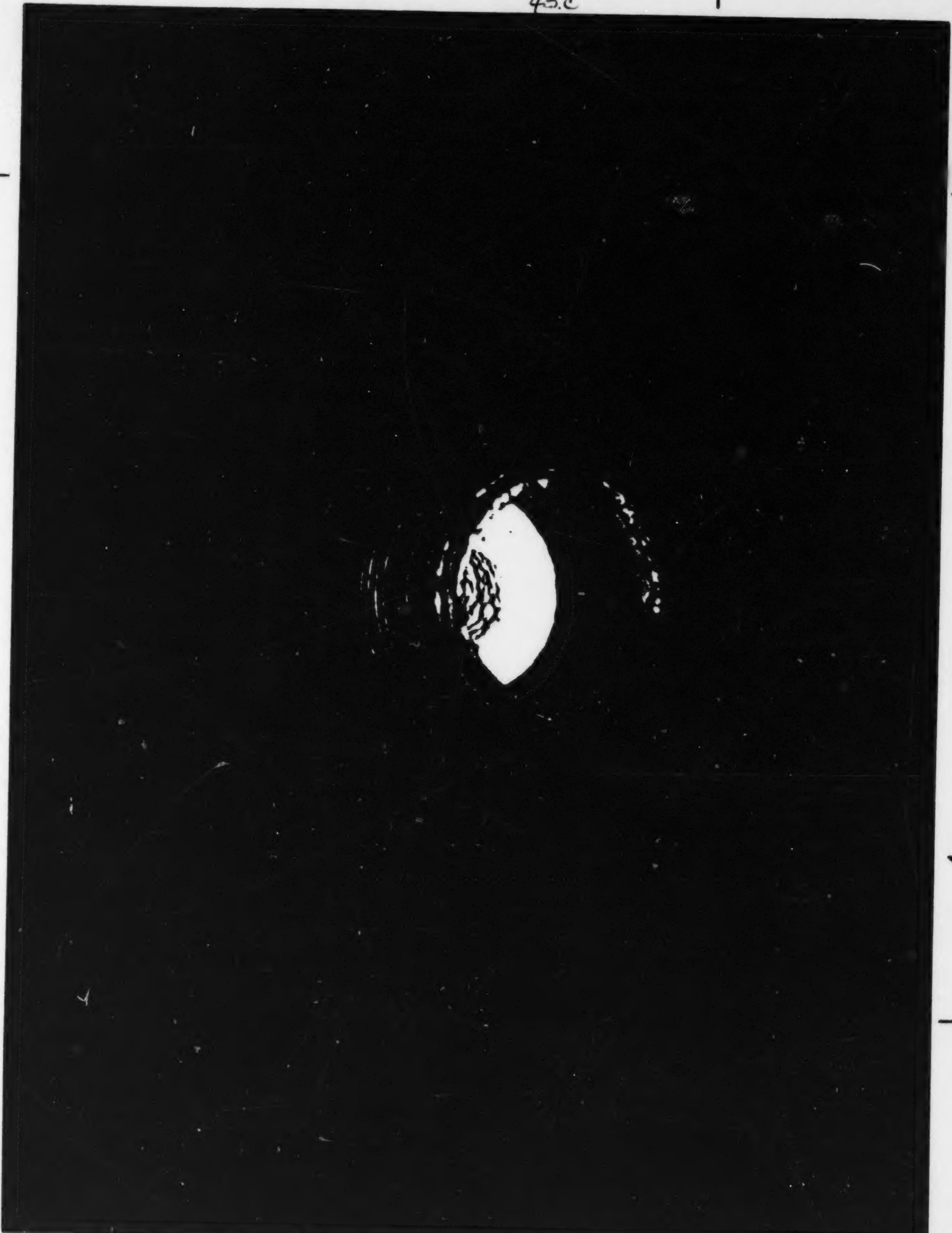


Fig. 5

43.C



Crop As Marked -Top-

Fi
52

43.d

Crop As Marked - top -

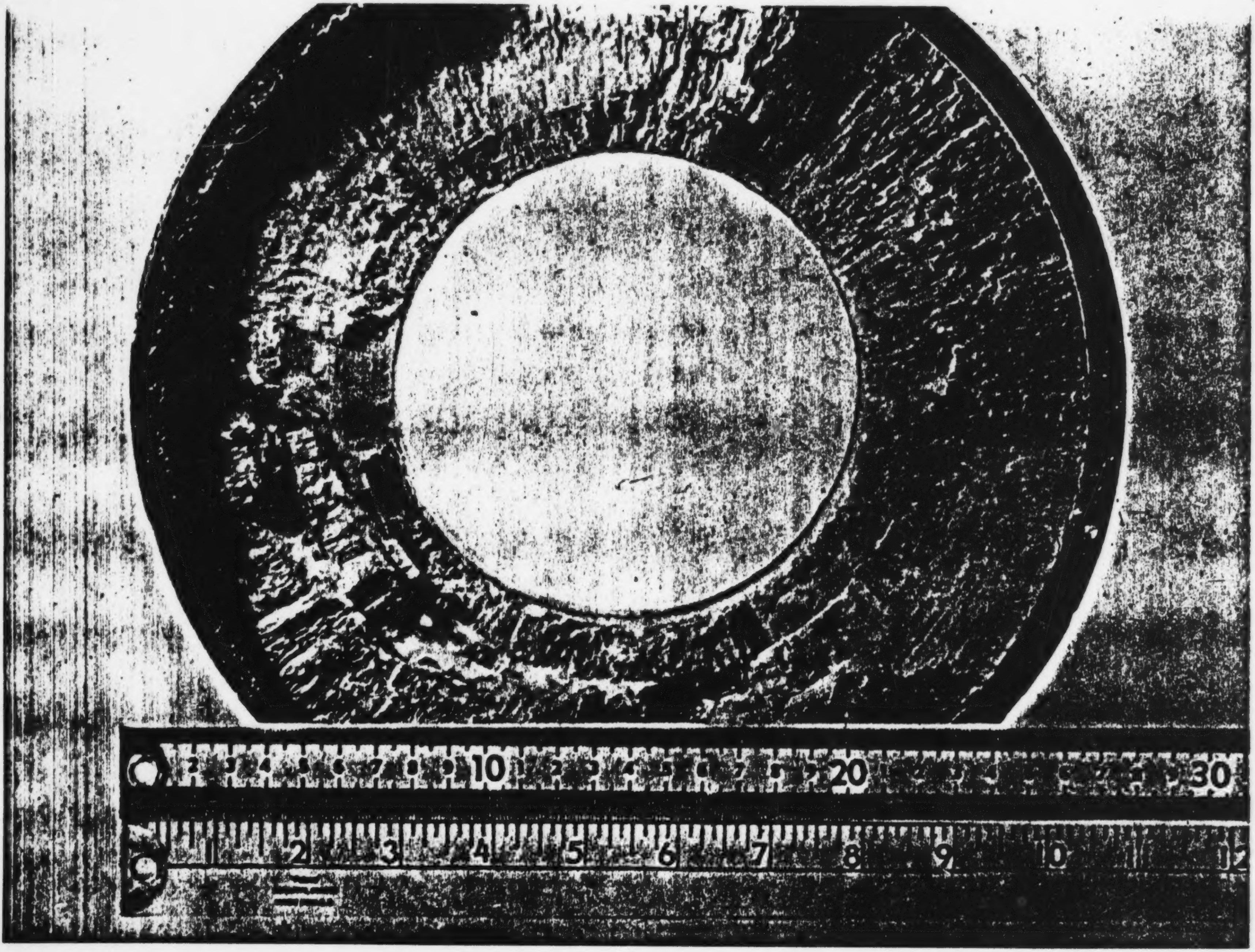


Fig 52

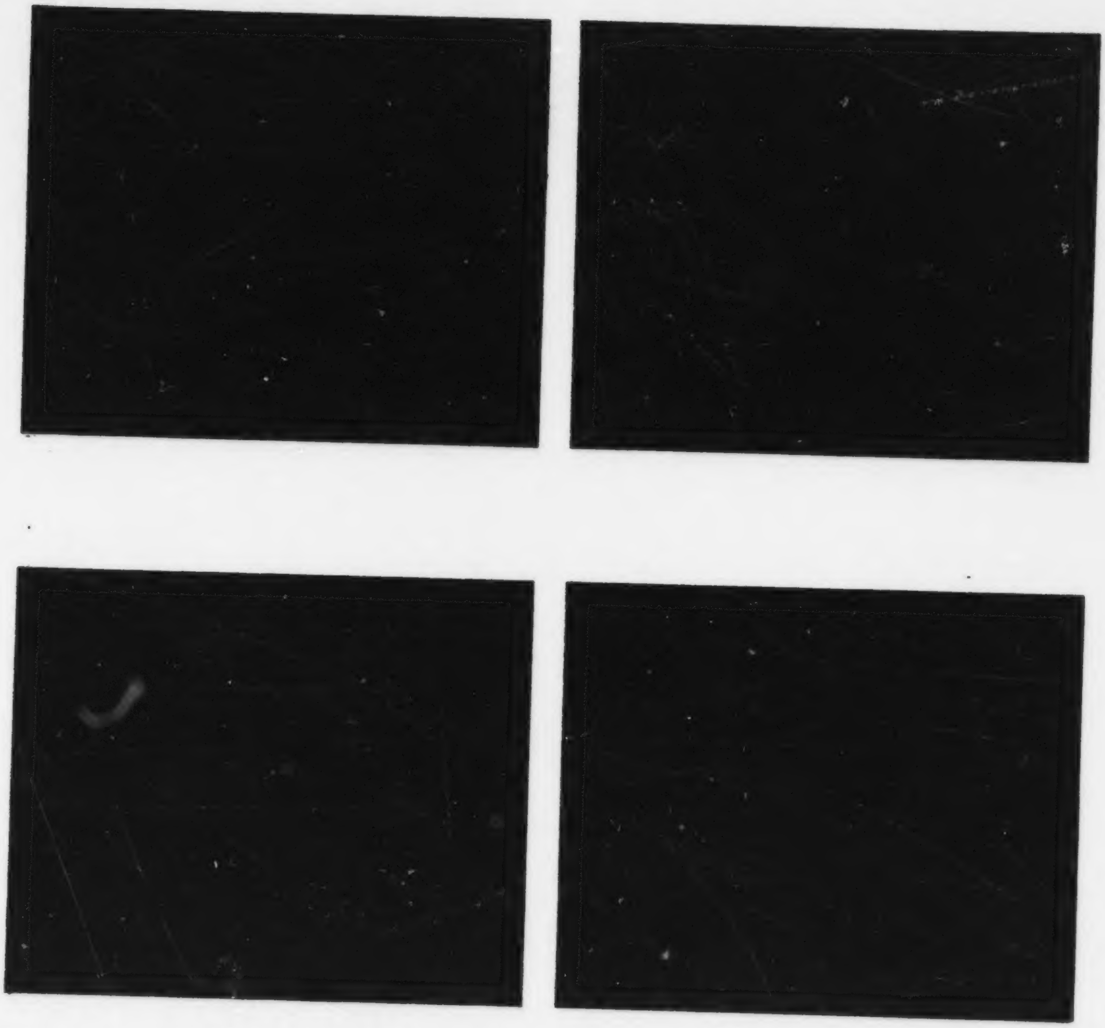


Fig. 6.2. Excessive $CaCO_3$ scaling resulting in loss of carrying capacity.

$$pH_s = A + B - \log [Ca^{++}] - \log \textit{total alkalinity}, \qquad (11)$$

where both A and B are constants related to the temperature and dissolved solids of the water. Values for A and B are tabulated in Tables 6.2 and 6.3.

The log of the calcium and alkalinity is obtained from Table 6.4.

Now, let's take as an example Chicago's tap water, which has the following characteristics:

Calcium (as $CaCO_3$), 88.0 mg/L
Total Alkalinity (as $CaCO_3$), 110.0 mg/L
Total dissolved solids, 170.0 mg/L
Case I: pH = 8.20; Temperature (T) = 25°C (77°F)
Case II: pH = 8.05; Temperature (T) = 57°C (135°F).

The step-by-step calculation of the LSI, using Tables 6.2 through 6.4, is as follows:

Case 1: pH = 8.2, T - 25°C (77°F)1

$$\begin{aligned} pH_s &= A + B - \log[Ca^{++}] - \log \text{alkalinity} \\ &= 2.00 + 9.81 - 1.94 - 2.04 \\ pH_s &= 7.83 \\ LSI &= pH - pH_s \\ &= 8.20 - 7.83 \\ &= 0.37 \end{aligned}$$

Case 2: pH = 8.05, T = 57°C (135°F)

If the same water used in Case 1 were heated to 57°C (135°F), as is typical in hot water tanks, the calculation of the LSI would be as follows:

$$\begin{aligned} pH_s &= 1.45 + 9.81 - 1.94 - 2.04 = 7.28 \\ LSI &= 8.05 - 7.28 = 0.77 \end{aligned}$$

Table 6.2 Constant "A" as function of water temperature

Water temperature °F	°C	Constant[a]
32	0	2.60
39.2	4	2.50
46.4	8	2.40
53.6	12	2.30
60.8	16	2.20
68	20	2.10
77	25	2.00
86	30	1.90
104	40	1.70
122	50	1.55
140	60	1.40
158	70	1.25
176	80	1.15

[a] Calculated from K_2 as reported by Harned and Scholes and K_2 as reported by Larson and Buswell. Values above 40°C have been extrapolated.

Source: *Federal Register*, 1980.

Table 6.3. Constant "B" as function of total filterable residue

Total dissolved solids (mg/L)	Constant
0	9.70
100	9.77
200	9.83
400	9.86
800	9.89
1000	9.90

Source: *Federal Register*, 1980.

Table 6.4. Logarithms of calcium and alkalinity concentrations

Ca^{+2} or Alkalinity (mg/L $CaCO_3$)	Log
10	1.00
20	1.30
30	1.48
40	1.60
50	1.70
60	1.78
70	1.84
80	1.90
100	2.00
200	2.30
300	2.48
400	2.60
500	2.70
600	2.78
700	2.84
800	2.90
900	2.95
1000	3.00

Source: *Federal Register*, 1980.

The results of the above calculations may be interpreted as follows:

Case I: LSI = +0.37, water tends to form a scale
Case II: LSI = +0.77, water definitely tends to form a scale.

The above examples show two important factors. First, they show the effect of the change in temperature and pH on the calculated LSI value. This demonstrates the need for accurate, onsite pH and temperature measurements. Second, a water which may deposit a thin protective scale in the distribution system at T = 25°C may form excessive scaling in the hot water system; therefore, the customer's hot water heaters may have to be descaled or replaced sooner than expected.

There are several limitations to the LSI. First, it is generally agreed that the LSI may only be used to estimate corrosive tendencies of waters within a pH range of 6.5 to 9.5. More importantly, the LSI only indicates the tendency for corrosion to occur. It is not a measurement of corrosivity.

Table 6.5 shows examples of water sources with different pH, pH_s, and Langelier index results. Pipe sections were physically examined to establish whether or not the water was corrosive. The results confirm that the LSI, by itself, does not indicate corrosiveness. It is, however, a valuable monitoring tool where a protective $CaCO_3$ film is being used or when used in conjunction with other indirect or direct corrosion monitoring methods.

A useful procedure for estimating the pH_s is an experimental method commonly called the Marble Test. In this test, duplicate samples of the water are collected. $CaCO_3$ (about 1 g/L) is added to one of the samples and shaken. After a time interval (usually 1 h or longer), aliquots from both samples are filtered and analyzed for alkalinity or pH. If the alkalinity or pH in the untreated sample is greater than that of the sample with $CaCO_3$, the water is supersaturated with $CaCO_3$ and may be scale forming. If the alkalinity or pH of the untreated sample is less than that of the $CaCO_3$-treated sample, the water is undersaturated with $CaCO_3$. If the alkalinities or pHs of the two samples are equal, the water is just saturated with $CaCO_3$.

Aggressive Index (AI). The AI was developed at the request of consulting engineers to govern the selection of the proper type (I or II) A-C pipe and to ensure long-term structural integrity. The AI is defined by the AWWA Standard C-400 as follows:

$$AI = pH + \log [(A)(H)] \tag{12}$$

where

pH = Hydrogen ion concentration, pH units
A = Total alkalinity, milligrams per liter as $CaCO_3$
H = Calcium hardness, mg/L as $CaCO_3$

The values obtained are interpreted as follows:

AI<10 → very aggressive (corrosive)
AI = 10–12 → moderately aggressive
AI>12 → nonaggressive

The AI is based on pH and the solubility of $CACO_3$. It is a simplified form of the LSI and only approximates the solubility of $CaCO_3$, not the corrosivity. However, it can be a useful tool in selecting materials or treatment options for corrosion control.

A sample calculation for the AI follows.

Given: pH = 7.4
A = 199 mg/L, as $CaCO_3$
H = 153 mg/L calcium hardness, as $CaCO_3$

Table 6.5. Corrosivity of waters versus the Langelier Saturation Index (LSI)

Source	pH	pH_s	LSI	Corrosive
Well water	7.30	7.20	+9.10	No
Well water	7.40	7.25	+0.15	Yes
Well water	7.10	7.14	−0.04	No
Well water	7.50	7.10	+0.40	Yes
Spring	7.30	8.08	−0.78	No
Deep well	6.30	8.27	−1.97	No
Deep well	6.80	7.88	−1.08	No
Spring	7.80	8.90	−1.10	No

Source: Singley, 1981.

Sample calculation:

$$\begin{aligned} AI &= pH + \log[(A)(H)] \\ &= 7.4 + \log(199 \times 153) \\ &= 7.4 + \log(199) + \log(153) \\ &= 7.4 + 2.3 + 2.1 \\ &= 11.8 \end{aligned}$$

In this example, the water should be classified as "moderately aggressive."

Other Corrosion Indices. Other corrosion indices commonly seen in the literature are

1. **Ryznar Stability Index (RSI)**—For this index, Ryznar used the same parameters as the LSI, but reversed the signs and doubled the pH_s, such that

$$RSI = 2\ pH_s - pH \tag{13}$$

   Ryznar also developed a curve based on these field observations, showing the scaling or corrosion of steel mains as a function of the index. This curve is shown in Fig. 6.3.

2. **Riddick's Corrosion Index (CI)**—Riddick's Index is based on actual field observations. The values obtained apply to the soft waters of the eastern seaboard of the United States, but not to the harder waters of the middle part of the country. The major contribution of this index is that it introduces factors other than $CaCO_3$ solubility, such as dissolved oxygen, chloride ion, and noncarbonate hardness, as well as the useful effect of silica.

3. **McCauley's Driving Force Index (DFI)**—This index is also based on $CaCO_3$ solubility and attempts to predict the amount of $CaCO_3$ that will precipitate. It can be useful in estimating the amount of precipitate that may be formed.

Table 6.6 lists the equation used to calculate each index, the analytical parameters required to perform the calculation, and the meaning of each index.

There have been attempts to use other water quality parameters to predict the tendency of a water to attack metal pipes. The classic studies of the Illinois State Water Survey by Larson, Sollo, and their co-workers have shown that other factors, such as the ratios of various anions, velocity, pH, and calcium ion concentration, affect the rates of corrosion of mild steel and cast iron. It was shown that increasing the Cl^- to HCO_3^- ratio, particularly above 0.3, increased the corrosion rate.

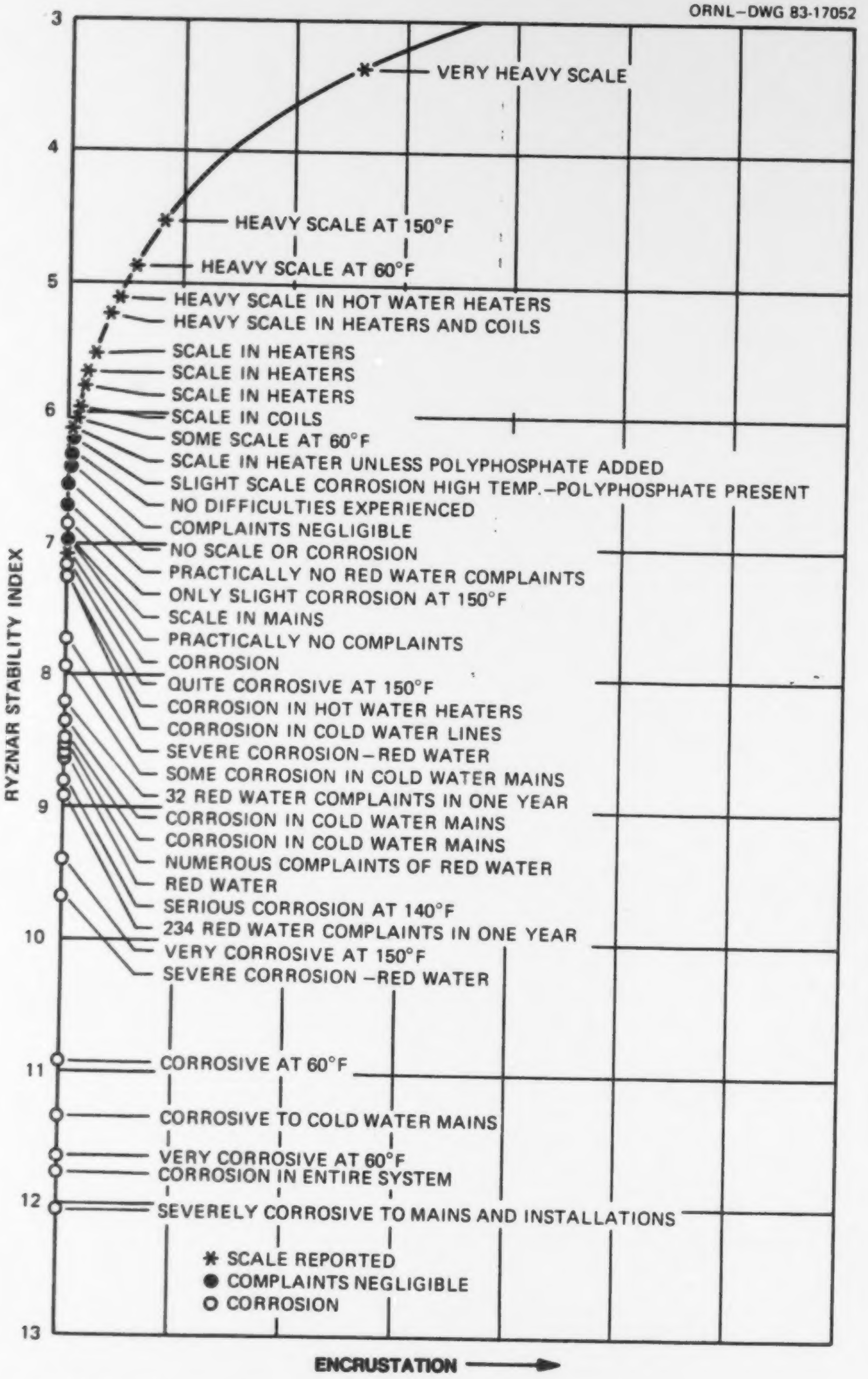


Fig. 6.3. Graphic representation of the various degrees of corrosion and encrustation.

Table 6.6. Summary of corrosion indices

Index	Equation	Parameters	Meaning
Langelier Saturation Index (LSI)	$LSI = pH - pH_s$	Total alkalinity, mg/L as $CaCO_3$ Calcium, mg/L as $CaCO_3$ Hardness, mg/L as $CaCO_3$ Total dissolved solids, mg/L Onsite pH Onsite temperature	LSI > 0 = Water is supersaturated; tends to precipitate $CaCO_3$ LSI = 0 = Water is saturated (in equilibrium); $CaCO_3$ scale is neither dissolved nor deposited LSI < 0 = Water is undersaturated; tends to dissolve solid $CaCO_3$
Aggressive Index (AI) (for use with asbestos cement)	$AI = pH + log[(A(H)]$	Total alkalinity, mg/L as $CaCO_3$ Hardness, mg/L as $CaCO_3$ Onsite pH	AI < 10 = Very aggressive AI = 10–12 = Moderately aggressive AL > 12 = Nonaggressive
Ryznar Stability Index (RSI)	$RSI = pH_s - pH$	Total alkalinity, mg/L as $CaCO_3$ Calcium, mg/L as $CaCO_3$ Hardness, mg/L as $CaCO_3$ Total dissolved solids, mg/L Onsite pH Onsite temperature	RSI < 6.5 = Water is supersaturated; tends to precipitate $CaCO_3$ 6.5 < RSI < 7.0 = Water is saturated (in equilibrium); $CaCO_3$ scale is neither dissolved nor deposited RSI > 7.0 = Water is undersaturated; tends to dissolve solid $CaCO_3$
Riddick's Corrosion Index (CI)	$\frac{75}{AlK}\left[CO_2+Y_2\left(Hardness-AlK\right)+Cl^-+2N\right]\times \left(\frac{10}{SiO_2}\right)\left(\frac{DO+2}{Sa+DO}\right)$	CO_2, mg/L Hardness, mg/L as $CaCO_3$ Alkalinity, mg/L as $CaCO_3$ Cl^-, mg/L N, mg/L DO, mg/L Saturation DO[a] (value for oxygen saturation), mg/L	CI = 0–5 Scale forming 6–25 Noncorrosive 26–50 Moderately corrosive 51–75 Corrosive 76–100 Very corrosive 101 + Extremely corrosive
Driving Force Index (DFI) $CaCO_3$	$\frac{Ca^{++}(\text{ppm})\times CO_3{=}(\text{ppm})}{K_{SO}\times 10^{10}}$	Calcium, mg/L as $CaCO_3$ $CO_3^=$ = mg/L as $CaCO_3$ K_{SO} = solubility product of $CaCO_3$	DFI < 1 = Water supersaturated; tends to precipitate DFI = 1 = Water saturated (in equilibrium); $CaCO_3$ scale is neither dissolved nor deposited DFI < 1 = Water undersaturated; tends to dissolve $CaCO_3$

[a] DO = dissolved oxygen

The presence of both calcium ion and alkalinity was shown to reduce the corrosion rate. These studies have led to a much better understanding of corrosion but have not resulted in a corrosion index.

Sampling and Chemical Analysis

Since corrosion is affected by the chemical composition of a water, sampling and chemical analysis of the water can provide valuable corrosion-related information. Some waters tend to be more aggressive or corrosive than others because of the quality of the water. For example, waters having a low pH (<6.0), low alkalinity (<40 mg/L), and high carbon dioxide (CO_2) tend to be more corrosive than waters with a pH greater than 7.0, high alkalinity, and low CO_2. Whether corrosion is occurring in the system, however, depends on the action of the water on the pipe material.

Most utilities routinely analyze their water (1) to ensure that they are providing a safe water to their customers and (2) to meet regulatory requirements. The 1980 Amendments to the NIPDWR require all community water supply systems to sample for certain "corrosive characteristics." Table 6.7 summarizes the sampling and analytical requirements of the 1980 amendments. The purpose of this sampling and analysis is to identify potentially corrosive waters throughout the country.

The amendments also require the water utility to identify the type of construction material used throughout the system, including service lines and home plumbing, and report the findings to the state. A water with "corrosive characteristics" may or may not be corrosive to a specific pipe material. Either way, sampling and analyzing for these "corrosive characteristics" can tell a utility if the water is potentially corrosive and alert the utility to potential problems.

Although the minimal sampling and analysis required by the 1980 amendments to the NIPDWR will provide an initial indication of the corrosive tendency of a finished water, additional sampling and chemical analysis performed over a period of time are necessary to indicate if corrosion is taking place and what materials are being corroded.

Table 6.7. 1980 Amendments to the NIPDWR: Sampling and analytical requirements
Individual states may add requirements

Parameters required	Sampling location	Number of samples	
		Water supply source	Number of samples per year
Alkalinity (mg/L as $CaCO_3$) pH (pH units) Hardness (mg/L as $CaCO_3$) Temperature (°C) Total dissolved solids (mg/L) Langelier or Aggressive Index[a]	Sample(s) are to be taken at one representative point as the water enters the distribution system	Groundwater only	1
		Surface water only or groundwater and surface water	2 samples, taken at different times of the year to account for seasonal variations in surface water supplies, such as mid-summer high temperatures and mid-winter low temperatures, or high flow and low flow conditions.

[a] The Langelier Saturation and Aggressive indices are calculated from the results of the chemical parameters. These indices are discussed on pages 43-48.

Source: *Federal Register*, August 1980.

Recommended Sampling Locations for Additional Corrosion Monitoring. It is generally desirable to collect water samples at the following locations within the system:

1. Water entering the distribution system (i.e., high-service pumping),
2. Water at various locations in the distribution system prior to household service lines,
3. Water in several household service lines throughout the system, and
4. Water at the customer's taps.

Water entering the distribution system at the plant can be conveniently sampled from the clearwell, the storage tank, or a sample tap on a pipe before or after the high-service pump.

To represent conditions at the customer's tap, "standing" samples should be taken from an interior faucet in which the water has remained for several hours (i.e., overnight). The sample should be collected as soon as the tap is opened.

A representative sample from the household service line (between the distribution system and the house itself) can be obtained by collecting a "running" sample from the customer's faucet after letting the tap run for a few minutes to flush the household lines. Frequently, the water temperature noticeably decreases when water in the service line reaches the tap. By letting the same faucet run for several minutes following the initial temperature change, the running water sample at the tap is representative of the water recently in the distribution main itself.

If a comparison of the sampling results shows a change in the water quality, corrosion may be occurring between the sampling locations.

Analysis of Corrosion By-product Material. Valuable information about probable corrosion causes can be found by chemically analyzing the corrosion by-product material. Scraping off a portion of the corrosion by-products, dissolving the material in acid, and qualitatively analyzing the solution for the presence of suspected metals or compounds can indicate the type or cause of corrosion. These analyses are relatively quick and inexpensive. If a utility does not have its own laboratory, samples of the pipe sections can be sent to an outside laboratory for analysis. The numerical results of these analyses cannot be quantitatively related to the amount of corrosion occurring since only a portion of the pipe is being analyzed. However, such analyses can give the utility a good overview of the type of corrosion that is taking place. The compounds for which the samples should be analyzed depend on the type of pipe material in the system and the appearance of the corrosion products. For example, brown or reddish-brown scales should be analyzed for iron and for trace amounts of copper. Greenish mineral deposits should be analyzed for copper. Black scales should be analyzed for iron and copper.

Sampling Technique. Since many important decisions are likely to be made based on the sampling and chemical analyses performed by a utility, it is important that care be taken during the sampling and analysis to obtain the best data. Samples should be collected without adding air, as air tends to remove CO_2 and also affects the oxygen content in the sample. To collect a sample without additional air, fill the same container to the top so that a meniscus is formed at the opening and no bubbles are present. The sample bottle should be filled below the surface of the water. To do this, slowly run water down the side of a larger container and immerse the sample bottle in the larger container. Cap the sample bottle as soon as possible.

Recommended Analyses for Additional Corrosion Monitoring. The parameters which should be analyzed for in a thorough corrosion monitoring program depend to a large extent on the materials present in the system's distribution, service, and household plumbing lines. In all cases, temperature and pH should be measured in situ (in the field). Dissolved gases, such as hydrogen sulfide (H_2S), oxygen, CO_2, and chlorine residual, also should be measured as part of a corrosion monitoring program. These parameters can be measured in situ or fixed for laboratory measurement. Total hardness, calcium, alkalinity, and TDS (or conductivity) must be measured if a protective coating of $CaCO_3$ is used for corrosion control or if cement-lined or A-C pipe is present in the system. These analyses are also necessary to calculate the $CaCO_3$-based corrosion indices. Heavy metals analyses should be conducted for the specific metals used in the distribution, service, and household plumbing lines. Measurement of anions, such as chloride and sulfate, may also indicate corrosion potential. Table 6.8 summarizes parameters recommended to be analyzed in a thorough corrosion monitoring program.

Frequency of analysis depends on the extent of the corrosion problems experienced in the system, the degree of variability in raw and finished water quality, the type of treatment and corrosion control practiced by the water utility and cost considerations.

Interpretation of Sampling and Analysis Data. Comparing sampling data from various locations within the distribution system can isolate sections of pipe that may be corroding. Increases in levels of metals such as iron or zinc, for instance, indicate potential corrosion occurring in sections of iron and galvanized iron pipe, respectively. The presence of cadmium, a minute contaminant in the zinc alloy used for galvanized pipe, also indicates the probable corrosion of a galvanized iron pipe.

Corrosion of cement-lined or A-C pipe is generally accompanied by an increase in both pH and calcium throughout the system, sometimes in conjunction with an elevated asbestos fiber count.

The following example illustrates the changes that can take place between a distribution system and a customer's tap. The analytical results in Table 6.9 were obtained from a small water supply system in Florida and the customer's hot water taps. In this case, A-C pipe is used throughout the distribution system. The home plumbing systems are mostly copper.

The water in the distribution system had no traces of copper or lead, and the LSI, calculated from the data as the water entered the distribution system, was slightly positive or potentially noncorrosive. Data in Table 6.9 show that high levels of copper from the household pipes and lead from the solder joints were being added to the customer's water through corrosion of the household plumbing. Further investigation of the household plumbing showed that the customer's hot water system was corroding.

Another example of the importance of data interpretation to an overall corrosion monitoring program is discussed below for A-C pipe. According to EPA's Drinking Water Research Division (DWRD), calculating the AI alone is not sufficient to predict the corrosive behavior of water to A-C pipe. For A-C pipe, additional sampling and data interpretations are recommended by DWRD for determining the corrosivity of a water to A-C pipe.

Table 6.8. Recommended analyses for a thorough corrosion monitoring program

In situ measurements	pH, temperature
Dissolved gases	Oxygen, hydrogen sulfide, carbon dioxide, free chlorine
Parameters required to calculate $CaCO_3$-based indices, or required for cement-lined or A-C pipe	Calcium, total hardness, alkalinity, total dissolved solids, fiber count (A-C pipe only)
Heavy Metals	
Iron or steel pipe	Iron
Lead pipe or lead-based solder	Lead
Copper pipe	Copper, lead
Galvanized iron pipe	Zinc, iron, cadmium, lead
Anions	Chloride, sulfate

Source: Environmental Science and Engineering, Inc., 1982.

Table 6.9. Water quality data from a Florida water utility

Sample location	Cu (mg/L)	Pb (mg/L)	Cl (mg/L)
Water entering distribution system	0	0	17
Water in distribution system	0	0	17
Water at customer's tap			
Sample set 1	5.0	0	3.0
Sample set 2	1.66	3.26	0.0

Source: Environmental Science and Engineering, Inc., 1982.

The following conditions indicate situations in which the water *may not attack* A-C pipe:

1. An initial AI above about 11;
2. No significant change in the pH or the concentration of calcium at different locations in the system;
3. No asbestos fibers *consistently* found in *representative* water samples after passage through A-C pipe;
    a. Significant asbestos fiber counts being found in *representative* water samples *at one time but not another* at a location where water flow is sufficient to clean the pipe of tapping debris (recent tapping can cause high fiber counts not related to pipe attack) and
    b. Significant asbestos fiber counts being found only in water samples collected from low-flow dead ends or from fire hydrants *(nonrepresentative samples)* and nowhere else in the system.

The following conditions indicate situations in which the water *may be attacking* A-C pipe:

1. An initial AI below about 11,
2. A significant increase in pH and the concentration of calcium at different locations in the system,
3. Significant asbestos fiber counts being found consistently in representative water samples collected from locations where (a) the flow is sufficient to clean the pipe of debris and (b) the pipe has been neither drilled nor tapped near or during the sampling period, and
4. Inlet water screens at coin-operated laundries become plugged with fibers.

The data obtained by sampling for corrosive characteristics can be used as a guide to water quality changes that might be required to reduce or control corrosion, such as pH adjustment or the addition of silicates or phosphates. Results of additional sampling, conducted after starting a corrosion control program, can indicate the success of any water quality changes.

6.2 DIRECT METHODS

Scale or Pipe Surface Examination

Examining the scale found inside a pipe is a direct monitoring and measuring corrosion control method that can tell a great deal about water quality and system conditions. It can be used as a tool to determine why a pipe is deteriorating or why it is protected and can be used to monitor the results of any corrosion control program. For example, a high concentration of calcium in a scale may shield the pipe wall from DO diffusion and thereby reduce the corrosion rate.

Methods used to examine scale on pipe walls include physical inspection [both macroscopic (human eye) and microscopic], X-ray diffraction, and Raman spectroscopy. Physical inspection is the only method of practical use to utility personnel, as X-ray diffraction and Raman spectroscopy require expensive, complicated instruments and experienced personnel to interpret the results.

Physical Inspection. Physical inspection is usually the most useful inspection tool to a utility because of the low cost. Both macroscopic (human eye) and microscopic observations of scale on the inside of the pipe are valuable tools in diagnosing the type and extent of corrosion. Macroscopic studies can be used to determine the amount of tuberculation and pitting and the number of crevices. The sample should be examined also for the presence of foreign materials and for corrosion at joints.

Utility personnel should try to obtain pipe sections from the distribution or customer plumbing systems whenever possible, such as when old lines and equipment are replaced. If a scale is not found in the pipe, an examination of the pipe wall can yield valuable information about the type and extent of corrosion and corrosion-product formation, (such as tubercles), though it may not indicate the most probable cause.

Examination under a microscope can yield even more information, such as hairline cracks and local corrosion too small to be seen by the unaided eye. Such an examination may provide additional clues to the underlying cause of corrosion by relating the type of corrosion to the metallurgical structure of the pipe.

Photographs of specimens should be taken for comparison with future visual examinations. High magnification photographs should be taken, if possible.

X-ray Diffraction. The diffraction patterns of X-rays of scale material can be used to identify scale constituents. The diffraction of the X-rays will produce a pattern on a film strip which can be compared with X-ray diffraction patterns of known materials. It is possible to identify complex chemical structures by their X-ray "fingerprint."

Raman Spectroscopy. Raman spectroscopy is a technique for identifying compounds present in corrosion scale and films without removing a metal sample. In Raman spectroscopy, an infrared beam is reflected off the surface to be analyzed, and the change in frequency of the beam is recorded as the Raman spectrum. This spectrum, which is different for all compounds, is compared with Raman spectra of known materials to identify the constituents of the corrosion film.

Raman spectroscopy and X-ray diffraction are useful in corrosion research and in corrosion studies where the nature of the scale is unknown. However, the cost of the analyses makes them too expensive to be used in solving most corrosion problems. Nearly all corrosion problems can be solved without the detailed information provided by these techniques.

Rate Measrements

Rate measurements are another method frequently used to identify and monitor corrosion. The corrosion rate of a material is commonly expressed in mils (0.001/inch) penetration per year (mpy). Common methods used to measure corrosion rates include (1) weight-loss methods (coupon testing and loop studies) and (2) electrochemical methods. Weight-loss methods measure corrosion over a period of time. Electrochemical methods measure either instantaneous corrosion rates or rates over a period of time, depending on the method used.

Coupon Weight-Loss Method. This method uses "coupons" or pipe sections as test specimens. It is used for field, pilot-, and bench-scale studies, provided the samples are cleaned and installed in the corrosive environment in such a way that the attack is not influenced by the pipe or container. The coupons usually are placed in the middle of the pipe section.

The weight of the specimen or coupon is measured on an analytical balance before and after immersion in the test water. The weight loss due to corrosion is converted to a uniform corrosion rate by the following formula (as per ASTM Method D2688 Method B):

$$\textit{Corrosion rate in mils/year} = \frac{534\ W}{DAT} \tag{14}$$

where
W = weight loss [milligrams (mg)],
D = density of specimen [grams per cubic centimeter (g/cm^3)],
A = surface area of specimen [square meters (m^2)], and
T = exposure time [hour (h)].

Coupon weight-loss test results do not measure localized corrosion but are an excellent method for measuring general or uniform corrosion. Coupons are most useful when corrosion rates are high so that weight loss data can be obtained in a reasonable time. The ASTM method above should be followed.

Following are lists of the advantages and disadvantages of the coupon method:

Advantages

1. provides information on the amount of material attacked by corrosion over a specified period of time and under specified operating conditions,
2. coupons can be placed in actual distribution systems for monitoring purposes, and
3. the method is relatively inexpensive.

Disadvantages

1. rate determinations may take a long time (i.e., months, if corrosion rates are moderate or low);
2. the method will not indicate any variations in the corrosion rate that occurred during the test;
3. the specimen or coupon may not be representative of the actual material for which the test is being performed;
4. the reaction between the metal coupon and the water may not be the same as the reaction at the pipe wall due to friction or flow velocity, since the coupon is placed in the middle of the pipe section; and
5. there may be difficulty in removing the corrosion products without removing some of the metal.

Loop System Weight-Loss Method. Another method for determining water quality effects on materials in the distribution system is the use of a pipe loop or sections of pipe. Either the loop or sections can be used to measure the extent of corrosion and the effect of corrosion control methods. Pipe loop sections can be used also to determine the effects of different water qualities on a specific pipe material. The advantage is that actual pipe is used as the corrosion specimen. The loop may be made from long or short sections of pipe.

Water flow through the loop may be either continuous or shut off with a timer part of the time to duplicate the flow pattern of a household. Pipe sections can be removed for weight-loss measurements and then opened for visual examination. This method is called the Illinois State Water Survey (ISWS) method and is an ASTM standard method (D2688, Method C) and should be followed closely.

Following are lists of the advantages and disadvantages of a loop system:

Advantages

1. actual pipe is used as the corrosion specimen;
2. loops can be placed at several points in the distribution system;
3. loops can be set up in the laboratory to test the corrosive effects of different water qualities on pipe materials;

4. the method provides information on the amount of material attacked by corrosion over a specified period of time and under specified operating conditions; and
5. the method is relatively inexpensive, as many corrosive effects can be examined visually.

Disadvantages

1. determination of corrosive rates can take a long time (i.e., months, if corrosion rates are moderate or low), and
2. the method does not indicate variations in the corrosion rate that occur during the test.

Electrochemical Rate Measurements. These methods are based on the electrochemical nature of corrosion of metals in water. An increasing number of these instruments are now on the market. However, they are relatively expensive and probably not widely used by smaller utilities. They are discussed here for completeness.

One type of electrochemical rate instrument has probes with two or three metal electrodes that are connected to an instrument meter to read corrosion in mpy. The electrode materials can be made of the material to be studied and inserted into the pipe or corrosive environment. For the other type, the loss of material over time is detected by an increase in the resistance of an electrode made of the metal of interest. Measurements made over a period of time can be used to estimate corrosion rates.

Following are lists of the advantages and disadvantages of electrical resistance measurements

Advantages

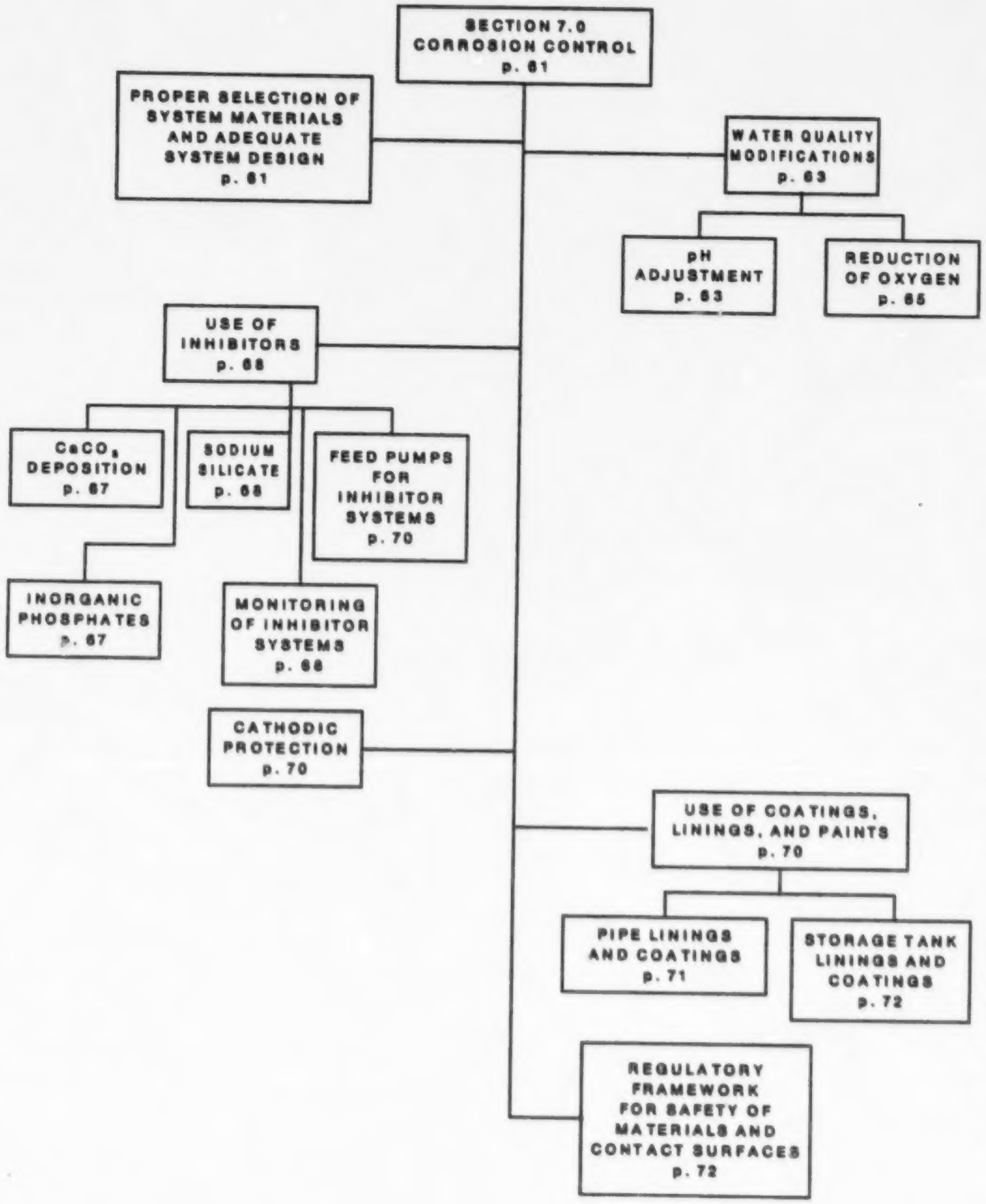
1. data may provide a graphic history of corrosion rate as it occurs,
2. measurements are rapid, and
3. short-term changes can be measured using linear polarization.

Disadvantages

1. probes may not represent actual material;
2. it is difficult to measure low corrosion rates by the resistance method;
3. they are useful only for metals;
4. the corrosion of a metal often depends on the amount of time it is exposed; therefore, the "instantaneous" corrosion rates given by these methods may not be the same as true long-term corrosion rates
5. as with all monitoring methods, many factors can affect the results; therefore, it is important not to jump to conclusions; and
6. trained, experienced personnel are needed to obtain and interpret data.

ORNL-DWG 83C-18349

INDEX TO SECTION 7


SECTION 7.0 CORROSION CONTROL p. 61
PROPER SELECTION OF SYSTEM MATERIALS AND ADEQUATE SYSTEM DESIGN p. 61
WATER QUALITY MODIFICATIONS p. 63
pH ADJUSTMENT p. 63
REDUCTION OF OXYGEN p. 65
USE OF INHIBITORS p. 66
$CaCO_3$ DEPOSITION p. 67
SODIUM SILICATE p. 68
FEED PUMPS FOR INHIBITOR SYSTEMS p. 70
INORGANIC PHOSPHATES p. 67
MONITORING OF INHIBITOR SYSTEMS p. 68
CATHODIC PROTECTION p. 70
USE OF COATINGS, LININGS, AND PAINTS p. 70
PIPE LININGS AND COATINGS p. 71
STORAGE TANK LININGS AND COATINGS p. 72
REGULATORY FRAMEWORK FOR SAFETY OF MATERIALS AND CONTACT SURFACES p. 72

7.0 CORROSION CONTROL

What can a water utility do to control corrosion in its water distribution system?

A schematic representation of a general approach to solving corrosion problems is shown in Fig. 7.1. To completely eliminate corrosion is difficult if not impossible. There are, however, several ways to reduce or inhibit corrosion that are within the capability of most water utilities. This section describes several methods most commonly used to control corrosion. The utility operator should use common sense in selecting the best and most economical method for successful corrosion control in a particular system. Because corrosion depends on both the specific water quality and pipe material in a system, a particular method may be successful in one system and not in another.

Corrosion is caused by a reaction between the pipe material and the water in direct contact with each other. Consequently, there are three basic approaches to corrosion control:

1. modify the water quality so that it is less corrosive to the pipe material,
2. place a protective barrier or lining between the water and the pipe, and
3. use pipe materials and design the system so that it is not corroded by a given water.

The most common ways of achieving corrosion control are to

1. properly select system materials and adequate system design;
2. modify water quality;
3. use inhibitors;
4. provide cathodic protection; and
5. use corrosion-resistant linings, coatings, and paints.

7.1 PROPER SELECTION OF SYSTEM MATERIALS AND ADEQUATE SYSTEM DESIGN

In many cases, corrosion can be reduced by properly selecting system materials and having a good engineering design. As discussed in Sect. 4.0, some pipe materials are more corrosion resistant than others in a specific environment. In general, the less reactive the material is with its environment, the more resistant the material is to corrosion. When selecting materials for replacing old lines or putting new lines in service, the utility should select a material that will not corrode in the water it contacts. Admittedly, this provides a limited solution since few utilities can select materials based on corrosion resistance alone. Usually several alternative materials must be compared and evaluated based on cost, availability, use, ease of installation, and maintenance, as well as resistance to corrosion. In addition, the utility owner may not have control over the selection and installation of the materials for household plumbing. There are, however, several guidelines that can be used in selecting materials.

First, some materials are known to be more corrosion resistant than others in a given environment. For, example, a low pH water that contains high DO levels will cause more corrosion damage in a copper pipe than in a concrete or cement-lined cast iron pipe. Other guidelines relating water quality to material selection are given in Table 4.3.

A good description of the proper selection of materials can be found in *The Prevention and Control of Water-caused Problems in Building Potable Water Systems*, published by the NACE.

Second, compatible materials should be used throughout the system. Two metal pipes having different activities, such as copper and galvanized iron, that come in direct contact with others can set up a galvanic cell and cause corrosion. The causes and mechanisms of galvanic corrosion are discussed in Sect. 3.0. As much as possible, systems should be designed to use the same metal throughout or to use metals having a similar position in the galvanic series (Table 3.1). Galvanic corrosion can be avoided by placing dielectric (insulating) couplings between dissimilar metals.

Preceding page blank

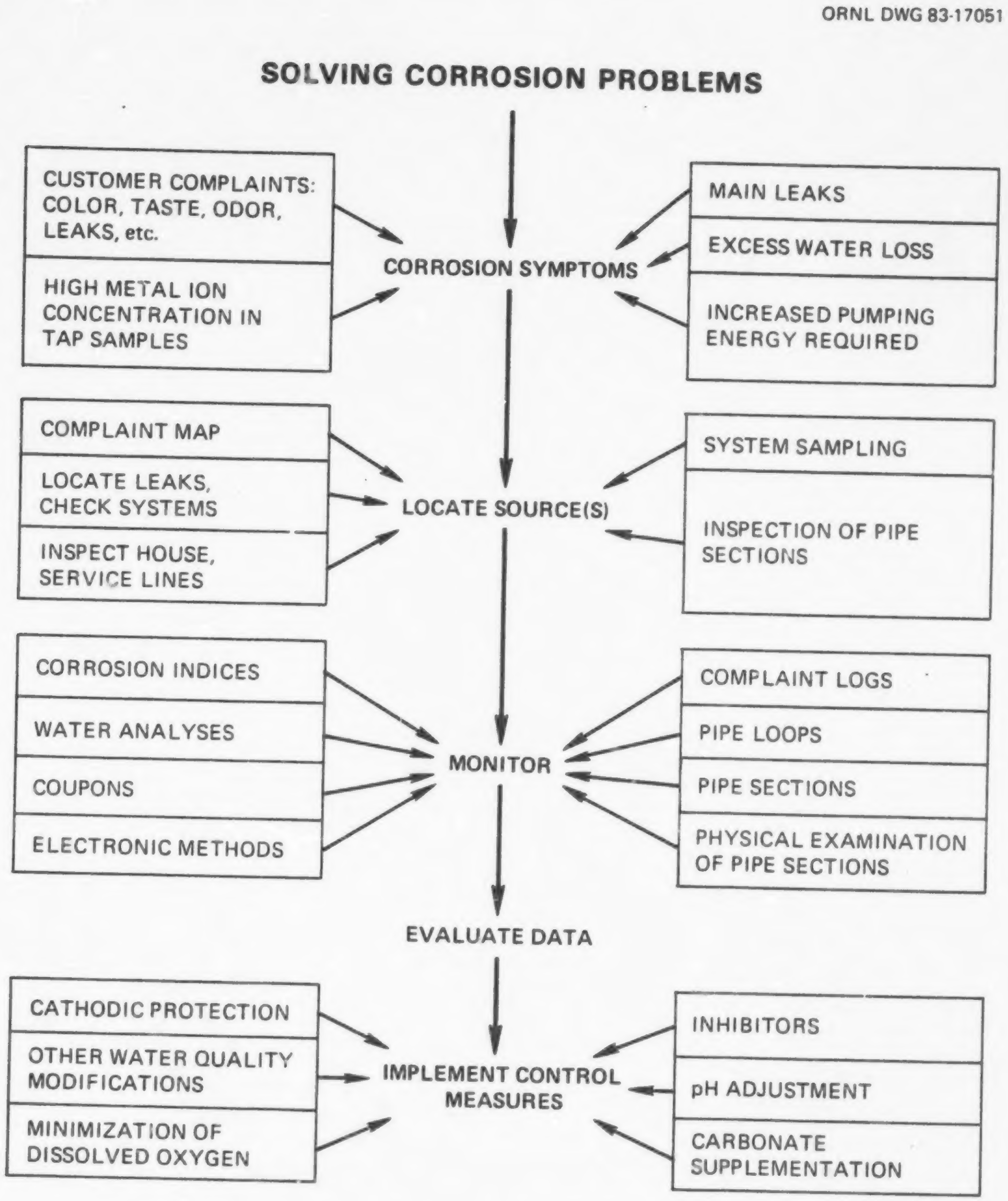

ORNL DWG 83-17051
SOLVING CORROSION PROBLEMS
CUSTOMER COMPLAINTS: COLOR, TASTE, ODOR, LEAKS, etc.
HIGH METAL ION CONCENTRATION IN TAP SAMPLES
CORROSION SYMPTOMS
MAIN LEAKS
EXCESS WATER LOSS
INCREASED PUMPING ENERGY REQUIRED
COMPLAINT MAP
LOCATE LEAKS, CHECK SYSTEMS
INSPECT HOUSE, SERVICE LINES
LOCATE SOURCE(S)
SYSTEM SAMPLING
INSPECTION OF PIPE SECTIONS
CORROSION INDICES
WATER ANALYSES
COUPONS
ELECTRONIC METHODS
MONITOR
COMPLAINT LOGS
PIPE LOOPS
PIPE SECTIONS
PHYSICAL EXAMINATION OF PIPE SECTIONS
EVALUATE DATA
CATHODIC PROTECTION
OTHER WATER QUALITY MODIFICATIONS
MINIMIZATION OF DISSOLVED OXYGEN
IMPLEMENT CONTROL MEASURES
INHIBITORS
pH ADJUSTMENT
CARBONATE SUPPLEMENTATION

Fig. 7.1. Steps toward solving corrosion problems.

The design of the pipes and structures is as important as the choice of construction materials. A faulty design may cause severe corrosion, even in materials that may be highly corrosion resistant. Some of the important design considerations include

1. avoiding dead ends and stagnant areas;
2. using welds instead of rivets;
3. providing adequate drainage where it is needed;
4. selecting an appropriate flow velocity;
5. selecting an appropriate metal thickness;
6. eliminating shielded areas;
7. reducing mechanical stresses;
8. avoiding uneven heat distribution;
9. avoiding sharp turns and elbows;
10. providing adequate insulation;
11. choosing a proper shape and geometry for the system;
12. providing easy access to the structure for periodic inspection, maintenance, and replacement of damaged parts; and
13. eliminating grounding of electrical circuits to the system.

Many plumbing codes are outdated and allow undesirable situations to exist. Such codes may even create problems, for example, by requiring lead joints in some piping. Where such problems exist, it may be helpful for the utility to work with the responsible government agency to modify outdated codes.

7.2 MODIFICATION OF WATER QUALITY

In many cases, the easiest and most practical way to make a water noncorrosive is to modify the water quality at the treatment plant. Because of the differences among raw water sources, the effectiveness of any water quality modification technique will vary widely from one water source to another. However, where applicable, water quality modification can often result in an economical method of corrosion control.

pH Adjustment

pH adjustment is the most common method of reducing corrosion in water distribution systems. pH plays a critical role in corrosion control for several reasons:

1. Hydrogen ions (H^+) act as electron acceptors and enter readily into electrochemical corrosion reactions. Acid waters are generally corrosive because of their high concentration of hydrogen ions. When corrosion takes place below pH 6.5, it is generally uniform corrosion. In the range between pH 6.5 and 8.0, the type of attack is more likely to be pitting.
2. pH is the major factor that determines the solubility of most pipe materials. Most materials used in water distribution systems (copper, zinc, iron, lead, and cement) dissolve more readily at a lower pH. Increasing the pH increases the hydroxide ion (OH^-) concentration, which, in turn, decreases the solubility of metals that have insoluble hydroxides, including copper, zinc, iron, and lead. When carbonate alkalinity is present, increasing the pH, up to a point, increases the amount of carbonate ion in solution. This may control the solubility of metals that have

insoluble carbonates, such as lead and copper. The cement matrix of A-C pipe or cement-lined pipe is also more soluble at a low pH. Increasing the pH is a major factor in limiting the dissolution of the cement binder and thus controlling corrosion in these types of pipes.

3. The relationship between pH and other water quality parameters, such as alkalinity, carbon dioxide (CO_2), and TDS, governs the solubility of calcium carbonate ($CaCO_3$), which is commonly used to provide a protective scale on interior pipe surfaces. To deposit this protective scale, the pH of the water must be slightly above the pH of saturation for $CaCO_3$, provided sufficient alkalinity and calcium are present.

pH adjustment alone is often insufficient to control corrosion in waters that are low in carbonate or bicarbonate alkalinity. A protective coating of $CaCO_3$, for instance, will not form unless a sufficient number of carbonate and calcium ions are in the water.

Some metals, notably lead and copper, form a layer of insoluble carbonate, which minimizes corrosion rates and the dissolution of these metals. In low alkalinity waters, carbonate ion must be added to form these insoluble carbonates. For such waters, soda ash (Na_2CO_3) or sodium bicarbonate ($NaHCO_3$) are the preferred chemicals generally used to adjust pH because they also contribute carbonate ($CO_3^=$) or bicarbonate ions (HCO_3^-). The number of carbonate ions available is a complex function of pH, temperature, and other water quality parameters. Bicarbonate alkalinity can be converted to carbonate alkalinity by increasing the pH. If carbonate supplementing is necessary to control corrosion in a water system, pH also must be carefully adjusted to ensure that the desired result is obtained.

The proper pH for any given water distribution system is so specific to its water quality and system materials that a manual of this type can provide only general guidance. If the water contains a moderate amount of carbonate alkalinity and hardness (approximately 40 mg/L as $CaCO_3$ or more of carbonate or bicarbonate alkalinity and calcium hardness), the utility should first calculate the LSI and/or AI to determine at what pH the water is stable with regard to $CaCO_3$. Other indices can be used to check this value. To start, the pH of the water should be adjusted such that the LSI is slightly positive, no more than 0.5 unit above the pH_s. If the AI is used as a guide, an initial AI value equal to or greater than 12 is desirable. If no other evidence is available, such as a good history of the effect of pH on the laying down of a protective coating of $CaCO_3$ or laboratory or field test results, then the LSI and/or AI provide a good starting point. Keeping the pH above the pH_s should cause a protective coating to develop. If no coating forms, then the pH should be increased another 0.1 to 0.2 unit until a coating begins to form. It is important to watch the pressure in the system carefully as too much scale build-up near the plant could seriously clog the transmission lines.

There is a strong tendency to overestimate the accuracy of the calculated values of the LSI or AI. Soft, low alkalinity waters cannot become supersaturated with $CaCO_3$ regardless of how high the pH is raised. In fact, raising the pH to values greater than about 10.3 is useless because no more carbonate ions can be made available. Excess hydroxide alkalinity is of no value since it does not aid in $CaCO_3$ precipitation.

For systems that do not rely on $CaCO_3$ deposition for corrosion control, it is more difficult to estimate the optimum pH. If lead and/or copper corrosion is a problem, adjusting the pH to values of from 7.5 to 8.0 or higher may be required. Practical minimum lead solubility occurs at a pH of about 8.5 in the presence of 30 to 40 mg/L of alkalinity. pH adjustment coupled with carbonate supplementing may be required to minimize lead corrosion problems.

Phosphates and other corrosion inhibitors often require a narrow pH range for maximum effectiveness. If such an inhibitor is used, consideration must be given to adjusting the pH to within the recommended range.

Chemicals commonly used for pH adjustment and/or carbonate supplementing, recommended dosages, and equipment requirements are summarized in Table 7.1. Schematics of typical chemical feed systems are shown in Fig. 7.2. The pH should be adjusted after filtration since waters having higher pHs need larger doses of alum for optimum coagulation.

Table 7.1. Chemicals for pH adjustment and/or carbonate supplementation

pH adjustment chemical	Typical feed rate	1 mg/L adds ___mg/L alkalinity[a]	Equipment required
Lime, as $Ca(OH)_2$	1–20 mg/L (8–170 lb/MG)	1.35	Quicklime-slaker, hydrated lime-solution tank, and feed pump with erosion-resistant lining as eductor
Caustic soda, NaOH (50% solution)	1–29 mg/L (8–170 lb/MG)	1.25	Proportioning pump or rotameter
Soda ash, Na_2CO_3	1–40 mg/L (8–350 lb/MG)	0.94	Solution tank, proportioning pump, or rotameter
Sodium bicarbonate, $NaHCO_3$	5–30 mg/L (40–250 lb/MG)	0.59	Solution tank, proportioning pump, or rotameter

[a] Caustic soda and lime add only hydroxide alkalinity. Soda ash and sodium bicarbonate add carbonate or bicarbonate alkalinity, depending on pH.

It is recommended that a corrosion monitoring program, such as that described in Sect. 6.0, be initiated to monitor the effects of this pH change over time. Evaluating the performance of chemical feed systems for pH adjustment is the key to an effective corrosion control program. Addition of lime, soda ash, or other chemicals for pH control can be evaluated by continuous readout pH recorders. The recorders monitor the pH of the water as it leaves the utility and can be wired to send a signal to the feed mechanism to add more or fewer chemicals as necessary. The pH levels at the outer reaches of the distribution system should be checked periodically for indications of any changes occurring within the system that might be due to corrosion.

Keep in mind that although pH adjustment can aid in reducing corrosion, it cannot eliminate corrosion in every case. However, pH adjustment is the least costly and most easily implemented method of achieving some corrosion control, and utilities should use it if at all possible.

Reduction of Oxygen

As explained in Sect. 3.0, oxygen is an important corrosive agent for the following reasons:

1. oxygen can act as an electron acceptor, allowing corrosion to continue;
2. oxygen reacts with hydrogen to depolarize the cathode and thus speeds up corrosive reaction rates; and
3. oxygen reacts with iron ions to form tubercles and leads to pitting in copper.

If oxygen could be removed from water economically, the chances of corrosion starting, and also the corrosion rate once it had started, would be reduced. Unfortunately, oxygen removal is too expensive for municipal water systems and is not a practical control method. However, there are ways to minimize the addition of oxygen to the raw water, particularly to groundwaters.

Often, aeration is the first step in treating groundwaters having high iron, hydrogen sulfide (H_2S) or CO_2 content. Though aeration helps remove these substances from raw water, it can also cause more serious corrosion problems by saturating the water with oxygen. In lime-soda softening plants for treating groundwater, the water is often aerated first to save on the cost of lime by eliminating free CO_2. Iron is oxidized and precipitated in this step, but this is incidental, because the

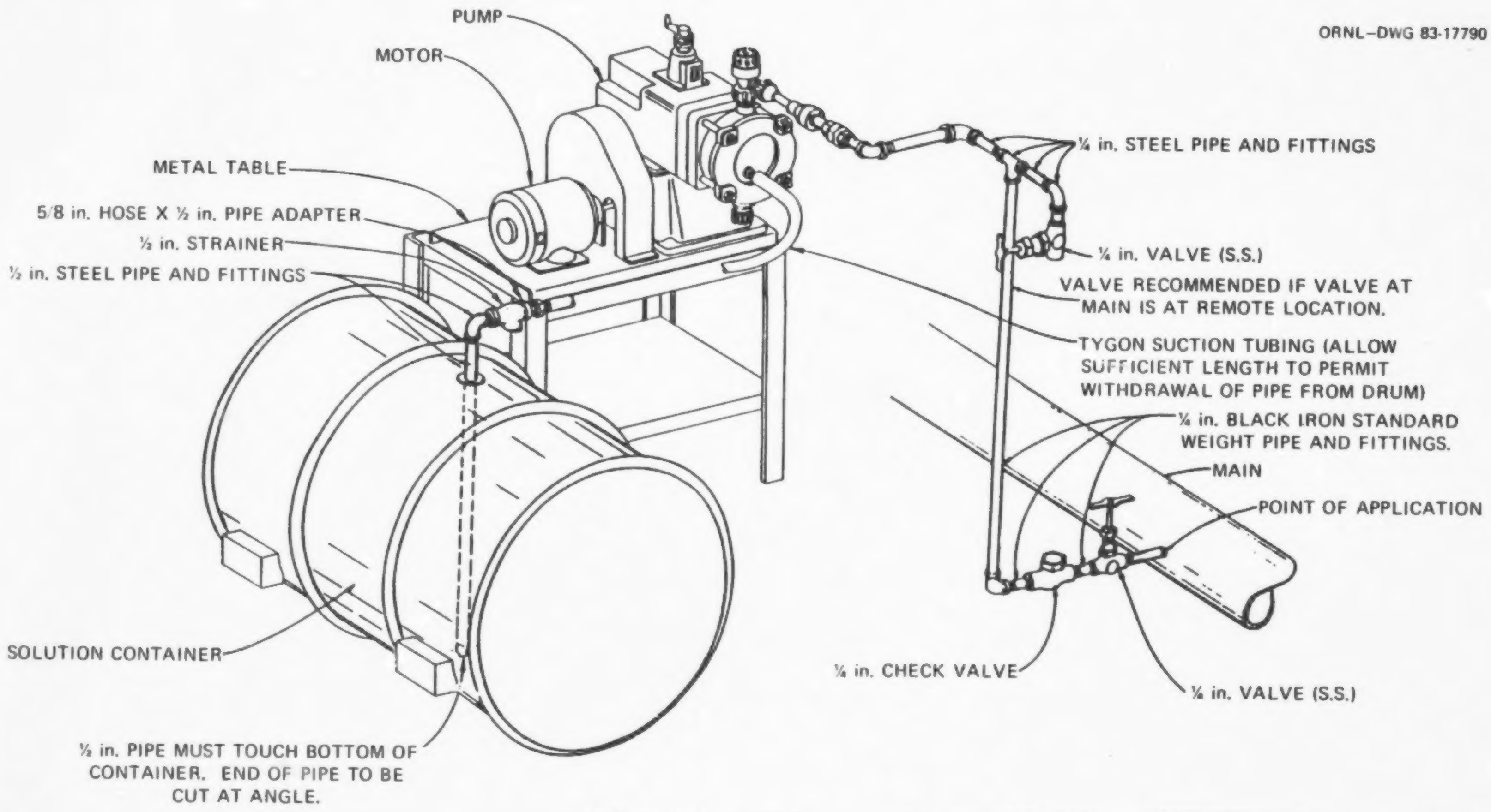

ORNL–DWG 83-17790
PUMP
MOTOR
METAL TABLE
5/8 in. HOSE X ½ in. PIPE ADAPTER
½ in. STRAINER
½ in. STEEL PIPE AND FITTINGS
SOLUTION CONTAINER
½ in. PIPE MUST TOUCH BOTTOM OF CONTAINER. END OF PIPE TO BE CUT AT ANGLE.
¼ in. STEEL PIPE AND FITTINGS
¼ in. VALVE (S.S.)
VALVE RECOMMENDED IF VALVE AT MAIN IS AT REMOTE LOCATION.
TYGON SUCTION TUBING (ALLOW SUFFICIENT LENGTH TO PERMIT WITHDRAWAL OF PIPE FROM DRUM)
¼ in. BLACK IRON STANDARD WEIGHT PIPE AND FITTINGS.
MAIN
POINT OF APPLICATION
¼ in. CHECK VALVE
¼ in. VALVE (S.S.)

Fig. 7.2. Schematic of a chemical feed system.

iron would be removed in the subsequent softening process even if the water were not aerated. The actual result is that DO increases to near saturation, and corrosion problems are increased. Thus, the attempt to save on lime addition may actually end up costing a great deal more in corrosion damage.

Measures that help keep the DO levels as low as possible include (1) sizing well pumps and distribution pumps so as to avoid air entrainment and (2) using as little aeration as possible when aerating for H_2S or CO_2 removal. This can be achieved by by-passing the aerators with part of the raw water. It has even been possible to completely eliminate the use of aerators if enough detention time is available in the reservoir so that enough oxygen can be absorbed at the surface to oxidize the H_2S or to let the CO_2 escape. DO levels can be kept as low as 0.5 to 2.0 mg/L by this method. This is low enough, in many cases, to reduce corrosion rates considerably.

7.3 USE OF INHIBITORS

Corrosion can be controlled by adding to the water chemicals which form a protective film on the surface of a pipe and provide a barrier between the water and the pipe. These chemicals, called inhibitors, reduce corrosion but do not totally prevent it.

The three types of chemical inhibitors commonly approved for use in potable water systems are chemicals which cause $CaCO_3$ scale formation, inorganic phosphates, and sodium silicate. There are currently several hundred commercially available products listed with various state and federal agencies for this use (see Sect. 7.6).

The success of any inhibitor in controlling corrosion depends upon three basic requirements. First, it is best to start the treatment at two or three times the normal inhibitor concentration to build up the protective film as fast as possible. This minimizes the opportunity for pitting to start before the entire metal surface has been covered by a protective film. Usually it takes several weeks for the coating to develop.

Second, the inhibitor may be fed continuously and at a sufficiently high concentration. Interruptions in the feed can cause loss of the protective film by re-dissolving it, and too low concentrations may prevent the formation of a protective film on all parts of the surface. Both interrupted feeding and low dosages can lead to pitting. On the other hand, excessive use of some alkaline inhibitors over a period of time can cause an undesirable build-up of scale, particularly in harder waters. The key to good corrosion inhibitor treatment is feed control.

Third, flow rates must be sufficient to continuously transport the inhibitor to all parts of the metal surface, otherwise an effective protective film will not be formed and maintained. Corrosion will then be free to take place. For example, corrosion inhibitors often can not reduce corrosion in storage tanks because the water is not flowing, and the inhibitor is not fed continuously. To avoid corrosion of the tanks, it is necessary to use a protective coating, cathodic protection, or both. Similarly, corrosion inhibitors are not as effective in protecting dead ends as they are in those sections of mains which have a reasonably continuous flow.

$CaCO_3$ Deposition

Under certain conditions, a layer of $CaCO_3$ will deposit on the surface of the pipe and serve as a protective barrier between the pipe wall and the water. This process is discussed in Sect. 6.0. It is mentioned again here because the addition of lime or alkalinity is a kind of inhibitor treatment.

Inorganic Phosphates

Phosphates are used to control corrosion in two ways: to prevent scale or excess $CaCO_3$ build-up and to prevent corrosive attack of a metal by forming a protective film on the surface of the pipe wall. Phosphates inhibit the deposition of a $CaC0_3$ scale on the pipe walls, which is an advantage only in the waters in which excessive scaling occurs. The mechanism by which phosphates form a protective film and inhibit corrosive attack, though not completely understood, is known to depend on flow velocity, phosphate concentration, temperature, pH, calcium, and carbonate levels.

There are several different types of phosphates used for corrosion control, including polyphosphates, orthophosphates, glassy polyphosphates, and bimetallic polyphosphates. Recent developments in corrosion control include the use of zinc along with a polyphosphate or orthophosphate.

Low dosages (about 2 to 4 mg/L) of glassy phosphates, such as sodium hexametaphosphate, have long been used to solve red water problems. In such cases, the addition of glassy phosphates masks the color, and the water appears clear because the iron is tied up as a complex ion. The corrosive symptoms are removed, but the corrosion rates are not reduced. Controlling actual metal loss requires dosages up to 10 times higher (20 to 40 mg/L) of the glassy phosphates. Other glassy phosphates which contain calcium as well as sodium are more effective as corrosion inhibitors. Adding zinc along with a phosphate has been successfully used to both inhibit corrosion and control red water at dosages of about 2 mg/L. The zinc phosphate treatment has also been used to eliminate rusty water, blue-green staining, lead pickup, and to reduce measured corrosion rates of metals.

The choice of a particular type of phosphate to use in a corrosion control program depends on the specific water quality. Some phosphates work better than others in a given environment. It is usually advisable to conduct laboratory or field tests of one or more phosphate inhibitors before long-term use is initiated. The case histories in Sect. 8.0 contain several examples of how such tests are performed and evaluated.

For smaller water utility plants [up to 1 million gallons per day (MGD)], phosphate feed solutions can be made up easily by batch as needed. A maximum phosphate solution concentration of 10 wt.% or 0.834 pound per gallon (lb/gal) is normally recommended. For a phosphate dose of 3 mg/L and a flow of 1 MGD, the volume of phosphate solution fed can be calculated as follows:

$$1\,MGD \times 3\,mg/L \times \frac{8.34\,lb/MG}{mg/L} \times \frac{1\,gal}{0.834\,lb} = \frac{30\,gal}{day} \qquad (15)$$

The equipment needed to feed phosphates to the water includes a 55-gal solution feed tank; a drum mixer; a chemical metering feed pump; and associated piping, feed lines, valves, and drains. The capital expenditure required is usually less than $2000 and is, therefore, within the means of most small water utilities.

Sodium Silicate

Sodium silicate (water glass) has been used for over 50 years to reduce corrosivity. The way in which sodium silicate acts to form a protective film is still not completely understood. However, it can effectively reduce corrosion and red water complaints in galvanized iron, yellow brass, and copper plumbing systems in both hot and cold water.

The effectiveness of sodium silicate as a corrosion inhibitor depends on water quality properties such as pH and bicarbonate concentration.

As a general rule, feed rates of 2 to 8 mg/L and possibly up to 12 mg/L of sodium silicate are sufficient to control corrosion in a system once a protective film is formed. Silicate has been found to be particularly useful in waters having very low hardness and alkalinity and a pH of less than 8.4. It is also more effective under higher velocity flow conditions. The equipment needed to feed sodium silicate is the same as that needed to add phosphate. The application of sodium silicate requires the use of solution feeders and small positive displacement pumps that deliver a specific volume of chemical solution for each piston stroke or impeller rotation. Figure 7.3 shows an example of a commercially available phosphate and/or silicate feed system for small water utilities.

Monitoring Inhibitor Systems

When phosphates or silicates are added to the water, samples should be collected at the far reaches of the system and analyzed for polyphosphates, orthophosphates, and sodium silicate, as appropriate. If no residual phosphate or silicate is found, the feed rate should be increased. Usually, ORNL–DWG 83-17789

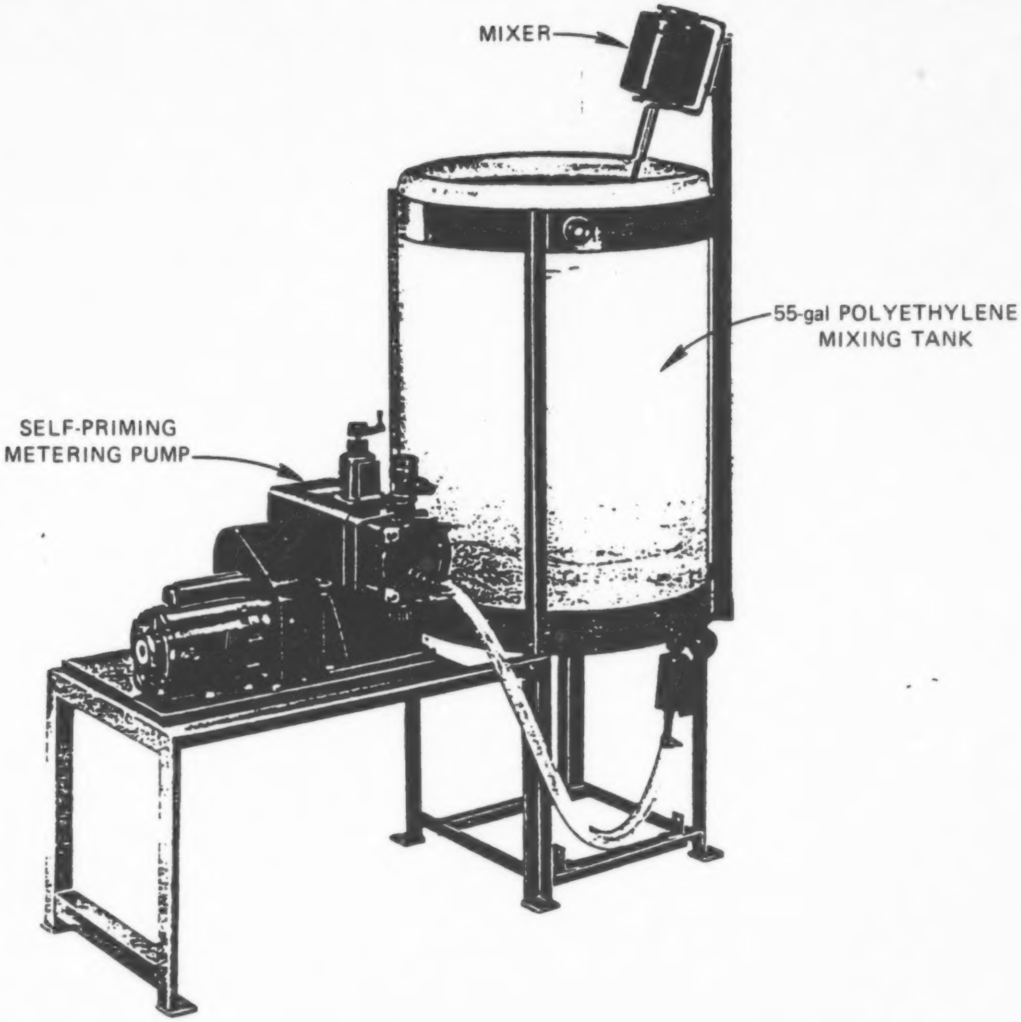


Fig. 7.3. Commercially available phosphate or silicate feed system.

only a residual is necessary to inhibit corrosion. If the concentration at the far reaches of the system is the same as that applied at the utility (e.g., 2 ppm), the utility may wish to decrease the chemical feed rate to save on costs for chemicals.

As previously discussed, initial inhibitor feed rates (for the first 2 weeks) should be 5 to 10 times higher than normal. During this time, water from the far reaches of the system should be sampled about twice a week to determine if corrosion products are leaching from the pipe wall. If the pipes are heavily tubercled, the tubercles are frequently broken loose by the inhibiting chemical. Where pitting has occurred, the system may be suddenly plagued with leaks as a result, and other corrective action must be initiated.

After the system has stabilized, sampling frequency can be reduced to about once a month or quarterly, depending on the resources available to the utility.

Feed Pumps for Inhibitor Systems

Chemical feed pumps. Most metering pumps used to add phosphate or silicate are positive displacement pumps. Pumping action for this type of pump is achieved by means of a piston, plunger, or diaphragm in which movement in one direction draws in a liquid through a valve, and movement in the opposite direction forces the liquid out through a second valve, causing a positive displacement of the liquid during each stroke of the unit. These types of pumps are generally used for chemical feeding when liquids heavier than water are being added. Chemical feed rates can be adjusted by changing the length and speed of the piston or diaphragm stroke. Usually, the water is pumped from a well or storage tank by centrifugal pumps throughout the distribution system. A signal can be wired from the centrifugal pump to the feed pump so that the feed pump is activated only when water is being pumped to the distribution system. Chemical feed pumps can be single or dual headed so that one or two chemicals can be added at the same time. The advantage of these pumps is that they are both accurate and reliable in feeding a specified amount of chemical to the system. The feed pumps should be calibrated about once a week to ensure that the desired amount of chemical is added.

7.4 CATHODIC PROTECTION

Cathodic protection is an electrical method for preventing corrosion of metallic structures. As discussed in Sect. 3.0, metallic corrosion involves contact between a metal and an electrically conductive solution which produces a flow of electrons or current from the metal to the solution. Cathodic protection stops the current by overpowering it with a stronger current from some outside source. This forces the metal that is being protected to become a cathode; that is, it has a large excess of electrons and cannot release any of its own. There are two basic methods of applying cathodic protection. One method uses inert electrodes, such as high-silicon cast iron or graphite, that are powered by an external source of direct current. The current impressed on the inert electrodes forces them to act as anodes, thus minimizing the possibility that the metal surface being protected will become an anode and corrode. The second method uses a sacrificial galvanic anode. Magnesium or zinc anodes produce a galvanic action with iron such that they are sacrificed (or corrode) while the iron structure they are connected to is protected from corrosion. This type of system is common to small hot water heaters. Another form of sacrificial anode is galvanizing where zinc is used to coat iron or steel. The zinc becomes the anode and corrodes, protecting the steel, which is forced to be the cathode.

The primary reason for applying cathodic protection in water utilities is to prevent internal corrosion in water storage tanks. Because of the high cost, cathodic protection is not a practical corrosion control method for use throughout a distribution piping system. Another limitation of cathodic protection is that it is almost impossible for cathodic protection to reach down into holes, crevices, or internal corners.

7.5 LININGS, COATINGS, AND PAINTS

Another way to keep corrosive water away from the pipe wall is to line the wall with a protective coating. These linings are usually mechanically applied, either when the pipe is manufactured or in the field before it is installed. Some linings can be applied even after the pipe is in service, though this method is much more expensive. The most common pipe linings are coal-tar enamels, epoxy paint, cement mortar, and polyethylene.

Water storage tanks are most commonly lined to protect the inner tank walls from corrosion. Common water tank linings include coal-tar enamels and paints, vinyls, and epoxy.

Although coal-tar-based products have been widely used in the past for contact with drinking water, currently there is concern at EPA about their use because of the presence of polynuclear aromatic hydrocarbons and other hazardous compounds in coal tar and the potential for their migration in water. Table 7.2 summarizes the most commonly used pipe linings and coatings and lists the advantages and disadvantages of each. Common water tank linings are summarized in Table 7.3.

Table 7.2. Pipe wall linings

Material	Use	Advantages	Disadvantages
Hot applied coal tar enamel	Lining for steel pipes (used in 50 to 80% of steel pipes in distribution systems)	Long service life (>50 years) Good erosion resistance to silt or sand Resistant to biological attachment	Need to reapply to welded areas Extreme heat may cause cracking Extreme cold may cause brittleness May cause an increase in trace organics in water
Epoxy	Lining for steel and ductile iron pipes (can be applied in the field or in a foundry)	Smooth surface results in reduced pumping costs Formulated from components approved by the Food and Drug Administration	Relatively expensive Less resistant to abrasion than coal tar enamel Service life <15 years
Cement mortar	Standard lining for ductile iron pipes, sometimes used in steel or cast-iron pipes	Relatively inexpensive Easy to apply (can be applied in place or in pipe manufacturing process) Calcium hydroxide release may protect uncoated metal at pipe joints	Rigidity of lining may lead to cracking or sloughing Thickness of coating reduces cross-sectional area of pipe and reduces carrying capacity
Polyethylene	Lining used in ductile iron and steel pipe (applied at foundry)	Long service life (50 years) Good erosion resistance to abrasives (silt and sand) Good resistance to bacterial corrosion Smooth surface results in reduced pumping costs	Relatively expensive

Source: Environmental Science and Engineering, Inc., 1981.

Table 7.3. Water storage tank linings and coatings

Material	Comments
Hot applied coal tar enamel	Most common coal-tar based coating used in water tanks; tends to sag or ripple when applied above the waterline when tank walls are heated
Coal tar paints	Most commonly used to reline existing water tanks; those paints containing xylene and naphtha solvents give the water an unpleasant taste and odor and should be used only above the waterline Other coal tar paints containing no solvent bases can be used below the waterline but should not be exposed to sunlight or ice; service life of 5 to 10 years
Coal tar epoxy paints	Less resistant to abrasion than coal tar enamel; can cause taste and odor problems in the water; and service life of about 20 years
Coal tar emulsion paint	Good adhesive characteristics, odorless, and resists sunlight degradation but not as watertight as other coal tar paints, which limits use below waterline
Vinyl	Nonreactive; hard, smooth surface; service life (about 20 years) is reduced by soft water conditions
Epoxy	Forms hard, smooth surface; low water permeability; good adhesive characteristics if properly formulated and applied
Hot and cold wax coatings	Applied directly over rust or old paint, short service life (about 5 years)
Metallic-sprayed zinc coating	Relatively expensive process that requires special skills and equipment, good rust inhibition, and service life of up to 50 years
Zinc-rich paints	Hard surface; resistant to rust and abrasion; relatively expensive
Chlorinated rubber paints	Used when controlling fumes from application of other linings is difficult or where their use is specified
Asphalt-based linings	Use is generally limited to relining existing asphalt-lined tanks

7.6 REGULATORY CONCERNS IN THE SELECTION OF PRODUCTS USED FOR CORROSION CONTROL

The need for government involvement in the use of corrosion control products stems from the possibility that potable water may become contaminated with potentially harmful substances when these products are used. Concerns about the public health risks focus on the residual amounts of water treatment chemicals in drinking water and the impurities found in them and on the potentially hazardous chemicals which could leach from materials and substances in contact with the water.

The EPA, operating in cooperation with the States and under the authority of the Safe Drinking Water Act, is charged with assuring that the public is provided with safe drinking water. Under the auspices of that charge, EPA assists the States and the public by providing scientific advice on the health safety of chemicals and other substances in and in contact with drinking water.

In rendering advisory opinions on corrosion control products, EPA does not "authorize," "approve," or otherwise control the use of such additives. However, in practice, many state health departments have relied heavily on EPA's opinions in their approval of products and equipment for use in treatment and distribution systems of public utilities. These opinions on product safety are handled through a voluntary product safety evaluation program at EPA.

Additionally, the National Academy of Sciences (NAS), under contract to ODW, recently published the first edition of the "Water Chemicals Codex," which sets recommended maximum impurity concentrations (RMICs) for harmful substances found in many common direct additives (bulk treatment chemicals). EPA has adopted the specifications in the "Codex" as informal guidelines for evaluating treatment chemicals, including corrosion inhibitors.

ORNL-DWG 83C-18350

INDEX TO SECTION 8

- SECTION 8.0 CASE HISTORIES p. 77
  - PINELLAS COUNTY WATER SYSTEM p. 77
  - MANDARIN UTILITIES p. 83
  - MIDDLESEX WATER COMPANY p. 85
  - SMALL HOSPITAL IN SIERRA NEVADA MTNS. p. 88
  - BOSTON METROPOLITAN AREA WATER SYSTEM p. 90
  - GALVANIZED PIPE AND EFFECTS OF COPPER—A COMPOSITE OF INCIDENTS p. 95
  - GREENWOOD COMMISSIONERS OF PUBLIC WORKS p. 98

Preceding page blank

8.0 CASE HISTORIES

This section presents several case histories of corrosion problems experienced by water utilities or commercial complexes responsible for providing potable water. Methods used to monitor and control corrosion in the distribution systems are presented. The case histories are as follows:

Case 1. Pinellas County Water System (PCWS), Pinellas County, Florida;
Case 2. Mandarin Utilities, Jacksonville, Florida;
Case 3. Middlesex Water Company (MWC), Woodbridge, New Jersey;
Case 4. A Small Hospital, Sierra Nevada, California;
Case 5. Boston Metropolitan Area Water System, Boston, Massachusetts;
Case 6. Galvanized Pipe and the Effects of Copper—A Composite of Incidents Experienced in California; and
Case 7. Greenwood Commissioners of Public Works (CPW), Greenwood, South Carolina.

Each case presents a corrosion problem unique to that utility or complex because of a specific water quality in a given environment. In each case, the source and the effects of the corrosion are different, and the control methods implemented also are unique to each system. However, the approaches to the problems are similar and relevant to most utilities, regardless of size or the nature of the corrosion problem. Each case is presented in some detail to emphasize the different steps used in corrosion control, such as investigating the extent and cause of the problem, sampling and analyzing to further evaluate the problem, testing different control alternatives, and implementing the corrective actions.

In addition to the case histories discused here, another excellent case history is the corrosion monitoring and control program implemented by Seattle, Washington. The Seattle experience has been described in several journals but is not included here because of the complexity and length of the study. Interested readers are referred to the report written by J.E. Courthene and G.J. Kirmeyer, "Seattle Internal Corrosion Control Plan—Summary Report," published in the AWWA Seminar Proceedings, June 25, 1978. The reader also will benefit by referring to the recent summary report released by EPA titled "Seattle Distribution System Corrosion Control Study, Vol. I, Cedar River Water Pilot Plant Study" (Hogt, Herrera, and Kirmeyer 1982).

Many corrosion problems can be solved by the water utility itself. Sometimes, however, in-house diagnosis may lead to wrong conclusions and ineffective treatment. There is often no substitute for consulting with experienced corrosion engineers, the local health department, or state water treatment personnel for assistance in solving corrosion problems.

8.1 PINELLAS COUNTY WATER SYSTEM

This study, excerpted from a paper presented by J.A. Nelson and F.J. Kingery at the AWWA Conference in June 1978, illustrates

1. the problems associated with copper pitting;
2. the effects of pH, CO_2, DO, and phosphate inhibitors on corrosion rates; and
3. the use of coupon tests to evaluate several control strategies.

Background

The PCWS, located on the west coast of Florida, includes two plants, serving about 350,000 consumers. Water production averages about 40 MGD. The water source is wells averaging 350 ft in depth from a typical lime rock formation known as the Floridan Aquifer. Water treatment originally involved aeration to remove H_2S, chlorination to give a free chlorine residual to 2.0 mg/L, and stabilization with sodium hydroxide to adjust the pH. Table 8.1 shows the results of a typical effluent water analysis from the plant.

Preceding page blank

Table 8.1. PCWS typical effluent water analysis

Parameter	mg/L
Total hardness as $CaCO_3$	214
Calcium as $CaCO_3$	198
Magnesium as $CaCO_3$	16
Total alkalinity as $CaCO_3$	200
Carbonate hardness as $CaCO_3$	200
Noncarbonate hardness as $CaCO_3$	14
Specific conductance	400
TDS	284
Iron as Fe	0.04
Carbon dioxide as CO_2	9
Chloride as Cl^-	22
Sulfate as SO_4	2
Turbidity (NTU)	0.12
pH	7.65
pH_s	7.45
Saturation index	+0.20

Source: AWWA Journal, June 1978, *AWWA Proceedings*.

Reports of leaking copper pipes in numerous homes and apartment complexes alerted PCWS personnel to its copper corrosion problem. To determine the cause and extent of the corrosion and correct deficiencies, the PCWS initiated an investigative monitoring program.

Initial Investigation and Monitoring Program

Procedure. To determine the extent of copper corrosion and acquire background information for evaluating future treatment modifications, the following investigation and monitoring program was instituted before any changes in plant operation were made:

1. Approximately 25 random samples were collected from customers' residences.
2. Twenty residents' homes were monitored weekly beginning in September 1974 for copper, pH, DO, and chlorine residual. Weekly sampling continued through May of 1980.
3. Drinking fountains throughout Pinellas County were monitored for copper content and found to average 1.35 mg/L.

Results. The results of the investigation indicated that not only was there a pitting problem, but also that copper levels averaged 1.5 mg/L. In some isolated points, 5.0 mg/L of copper was found in water left standing overnight in customers' copper service lines. It became evident that it was necessary to reduce the pitting action and to reduce the copper level to under 1.0 mg/L.

Testing of Alternative Control Methods

Alternative 1: Adjustment of pH and CO_2

Procedure. To determine the degree of copper corrosion caused by low pH and thus high CO_2, the pH was increased to 7.9 by increasing the sodium hydroxide feed to 18 mg/L. Raising the pH reduced the CO_2 level from about 8.0 mg/L to 3.0 mg/L.

Results. The average copper content was reduced by 0.33 mg/L, but after 1 month, excessive scaling of pipes and pumps occurred throughout the plant near the point of chemical addition, and pH had to be reduced to 7.65.

This demonstrates that in an effort to control an existing problem, one frequently creates another, possibly worse, problem. Especially when using pH adjustment as a means of controlling corrosion, $CaCO_3$ solubility must be kept in mind. A typical water shows a Langelier shift of +0.8 unit when heated from 60°F (15.5°C) to 140°F (60°C). By adjusting to slightly positive in the distribution system, the utility frequently runs the risk of scaling consumer water heaters or other equipment in the system.

Alternative 2: Reduction of DO

Procedure. To determine the degree of copper corrosion caused by DO, the Plant 1 aerators were by-passed. Plant 1 supplies one area of distribution exclusively before blending with water from Plant 2 about 10 miles away at a 20-million gallon storage and booster station.

The service area fed by Plant 1 consisted of 5 of the original 20 distribution sample points and provided an excellent opportunity to compare results of further treatment changes. Also, a 50-ft coil of ½-in. copper tubing was placed in the effluent water of each plant for additional monitoring.

Results. After by-passing the Plant 1 aerators, the DO of the finished water was reduced from 7.5 to 0.5 mg/L. Sodium hydroxide was increased to 24 mg/L in oder to maintain a pH of 7.65.

Daily samples were taken of both plant effluents and within the distribution system. The copper level in the Plant 1 effluent at the 50-ft copper tubing dropped from 2.5 mg/L to an average of 0.15 mg/L. Oxygen levels averaged 1.0 mg/L within the distribution system as a result of an open clearwell and tank storage.

Alternative 3: Sodium Zinc Phosphate (SZP) Pilot Test

SZP was considered as a possible inhibitor of copper corrosion. Figure 8.1 illustrates methods used for a 3-month pilot test.

Procedure. A micropump was used to feed a stock solution of SZP at the rate of 1.0 mg/L into the water flowing through a 50-ft coil of ½-in. copper tubing. Water was controlled at 1½ ft/s by use of a constant-head device. An untreated section of copper pipe was used as a control.

Water dosed with SZP was allowed to flow through one section of copper tubing for 8 h. Both the untreated and dosed water were then turned off and allowed to stand in the copper pipe for up to 24 h before testing. The CO_2 content was 9.0 mg/L, and oxygen averaged 7.5 mg/L throughout the test period.

Samples were taken from each tap and analyzed for their copper content. Sequestering with 2.5 mg/L of SZP for 2 d preceded the test run.

Results. Over a period of 90 d, the average copper reduction was 0.5 mg/L, approximately 30%.

Alternative 4: SZP Started on Plant 1

Procedure. Based on the results of the pilot test using SZP to control copper corrosion, it was decided to use this inhibitor in water from Plant 1 for a 3-month trial period.

The SZP was fed at the rate of 1.0 mg/L using a diaphragm proportioning pump. Because a lower pH was recommended, the pH of the finished water was reduced to 7.4, which increased the CO_2 to 14.0 mg/L.

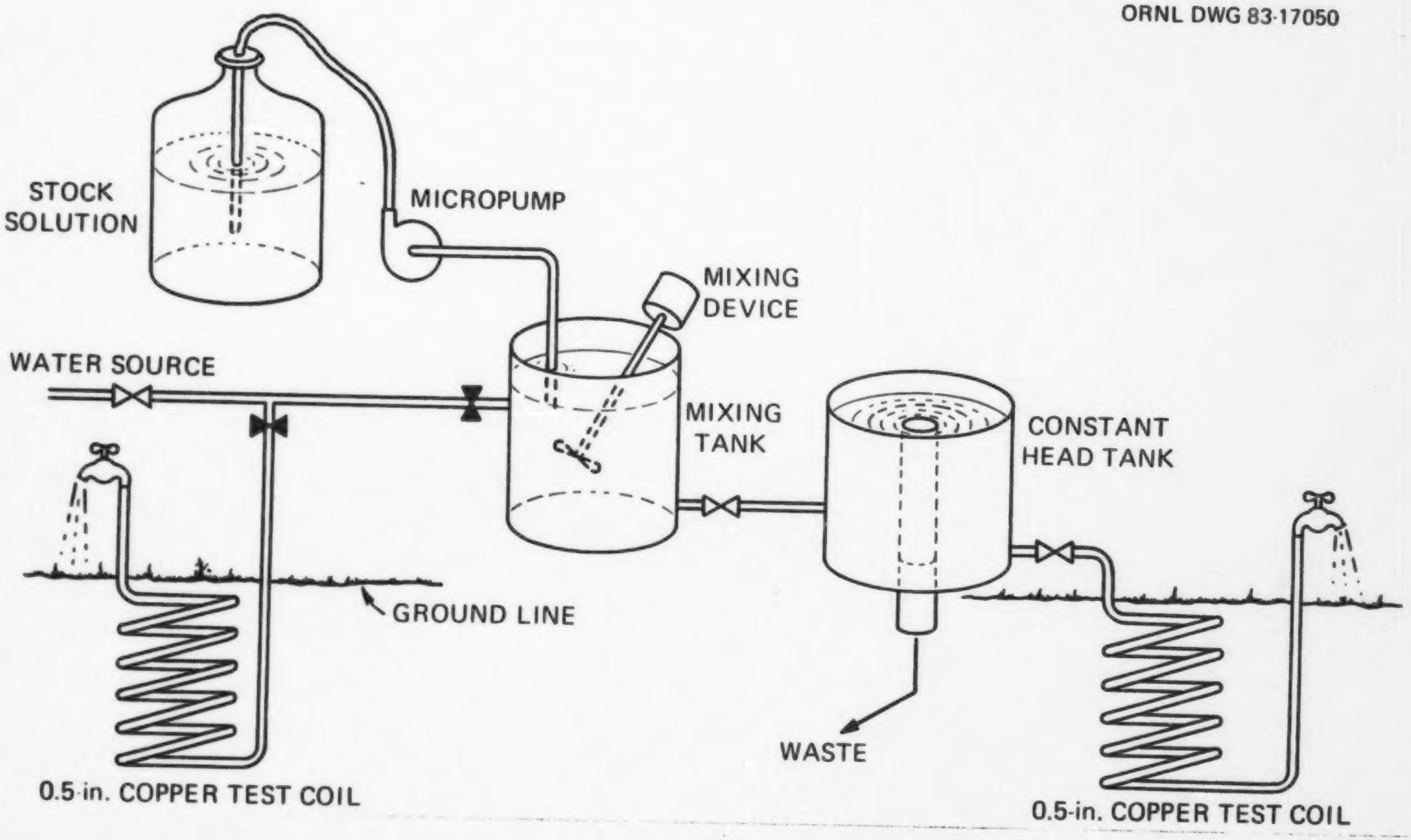

ORNL DWG 83-17050
STOCK SOLUTION
MICROPUMP
MIXING DEVICE
WATER SOURCE
MIXING TANK
CONSTANT HEAD TANK
GROUND LINE
WASTE
0.5-in. COPPER TEST COIL
0.5-in. COPPER TEST COIL

Fig. 8.1. Inhibitor pilot test.

The distribution sampling points that had been selected previously were monitored weekly for copper content. Over a period of 3 months, the average copper content of these 65 samples was 1.51 mg/L.

Results. Results of the test were questionable because copper levels did not compare with those of the pilot test program. The pilot test resulted in 1.10 mg/L of copper, while the actual results of monitoring points averaged 1.51 mg/L of copper, about a 30% difference.

Excluding minor variations in plant operation, it is probable that the lower pH and higher CO_2 content were the principal reasons for the higher copper levels recorded at the distribution monitoring stations. Higher feed rates of SZP may be necessary to achieve favorable results.

Alternative 5: Zinc Orthophosphate (ZOP)

To find the best inhibitor of copper corrosion, ZOP was investigated in a bench study using both mild steel and copper coupons. A 30-d test using both SZP and ZOP was compared with conventional stabilization using sodium hydroxide (NaOH).

Procedure. The test was based on one reported by E.D. Mullen in the *AWWA Journal* (August 1974), except that in this test the copper and mild steel coupons were used simultaneously.

The two test units were plastic assemblies of three cylindrical cells each, connected in series. The inlet cell held the copper and steel control coupons; the water then flowed to the center cell for chemical addition and mixing and then through the last cell holding the test copper and steel coupons.

Both units were connected to the same plant effluent line that was fitted with ½-gallon-per-minute (gpm) ball valves for flow control.

Inhibitors were fed to the center mixing cell using a controlled siphon. The chemical feed rates and flow rates were checked daily for 30 d.

Results. Figure 8.2 compares the corrosion rates of each inhibitor. ZOP reduced the corrosion rate of copper by 51%, and SZP reduced the corrosion rate of copper by 5%.

ORNL DWG 83-17049

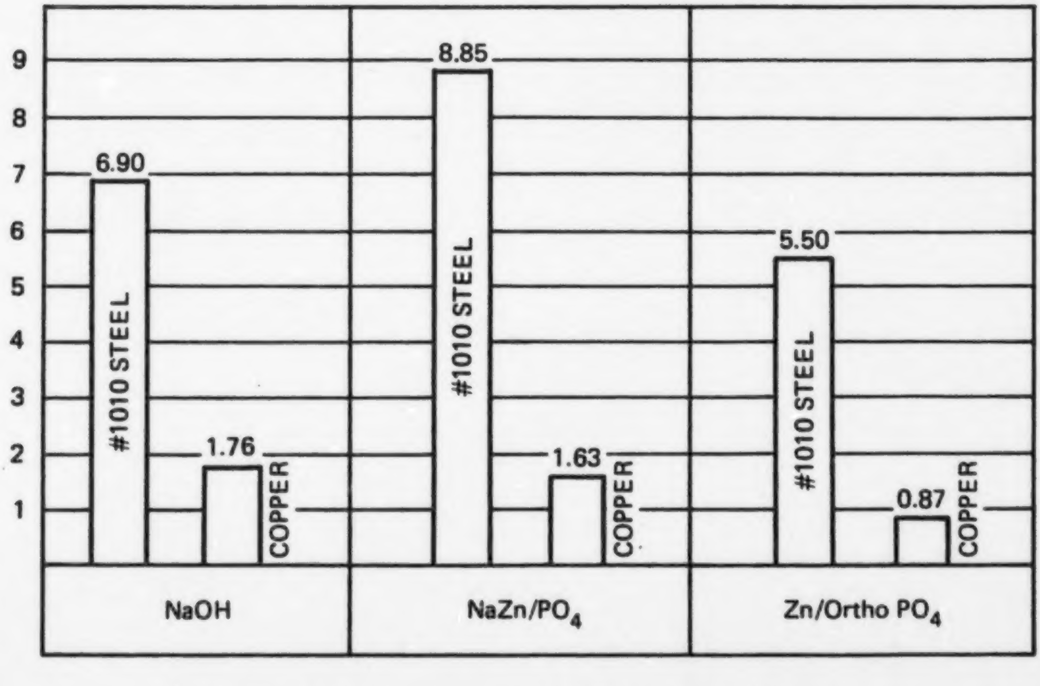


Fig. 8.2. Coupon corrosion rates of NaOH and inhibitors.

Additional Studies

To evaluate the effects of lime-softened water on copper pipe, a study was conducted to compare samples of pipe from a neighboring city, which has used lime softening for over 40 years, to the PCWS pipe.

A number of miscellaneous samples of copper tubing and water meter screens were sent to The University of Florida in Gainesville, Florida, for X-ray examination to determine corrosion products. It was possible to separate the deposits on the meter screens into several layers, varying in color and texture.

The screens generally had a yellowish-white outer deposit and bluish or greenish underlying deposits. Although it was not possible to identify all the compounds present in the reaction products on the various samples of pipe and screen, several observations could be made.

1. The most significant difference in the composition of deposits on the screens from a lime-softened water compared to that of the PCWS is the amount of calcium present. Calcium was present in far greater amounts on the softened-water screens. Presumably, the calcium is largely in the form of carbonate. There is no certain way of determining exactly when or at what rate calcium was deposited. However, calcium was a major constituent in all layers of the deposits of the softened-water screens examined.

2. The relative lack of calcium on the PCWS screens suggests the absence of protective $CaCO_3$ films over some extended period. This would explain the relatively higher corrosion observed on the PCWS screens.

3. The use of ZOP appears to favor deposition of calcium as well as zinc and phosphorus.

Current corrosion control methods. After full-scale implementation of phosphate inhibitor treatment, the Pinellas County utility found that its copper corrosion problem could be controlled just by adjusting the pH and reducing DO in the system. Currently, the utility carefully controls the pH at 7.65. The water by-passes the aerators completely and flows directly into the clearwell under the aerators. This reduces H_2S and maintains the DO level at less than 1 mg/L, which does not appear to be corroding the copper in the system.

Conclusions

Several suggestions are offered by PCWS utility personnel for monitoring the extent of corrosion within the distribution system.

1. Collect weekly samples from several remote sections of the distribution system; run tests for pH, alkalinity, specific conductance, iron, and copper and compare with plant effluent analyses for deterioration of water quality.

2. Check copper meter screens; observe any discoloration or corrosion products. Submit samples for X-ray analysis if needed.

3. Check with local plumbing shops for frequency and types of plumbing repairs.

4. Examine pipe coupons where large taps are made; inspect and gage for a protective calcium layer.

5. Purchase and install corrosivity meters, now available, which can accurately measure corrosion rate.

6. Use both copper and mild steel coupons at the plant and within the distribution system. The AWWA's Water Quality Goals suggest a weight loss of 5 milligrams per square centimeter (mg/cm^2) for a 90-d period, using galvanized wrought-iron coupons. The rate, when calculated as mils per year and compared to mild steel, corresponds to a corrosion rate of 1.0 mpy. (Generally accepted guidelines consider that 5 to 10 mpy will provide an acceptable water quality and corrosion protection.)

8.2 MANDARIN UTILITIES

This case history, which summarizes a study performed by consultants to the utility, illustrates (1) how a small utility company solved a copper corrosion ("black water") problem and (2) the benefits of actively logging and investigating consumer complaints about corrosion.

Background

Mandarin Utilities is a private utility in Jacksonville, Florida, that provides drinking water to several residential and commercial subdivisions.

The Mandarin Utilities system consists of six plants located throughout the utility's service area, with a total production of about 1.5 MGD. The water source for the plants is groundwater from wells averaging 175 ft in depth from the Floridan Aquifer. Corrosion problems were occurring only in the area served by the Pickwick Park plant, which produces about 0.9 MGD.

Currently, treatment consists of aeration to remove about 1 mg/L of dissolved H_2S and chlorination before storage and distribution. Prior to November 1980, no aeration facilities for removing H_2S existed at the Pickwick Park plant. All other plants serving the Mandarin system had aerators installed for H_2S removal. During this time, customers served by the Pickwick Park plant experienced severe "black-water" corrosion of their copper household plumbing as a result of the reaction of sulfides with the copper plumbing. Elemental sulfur, which forms when sulfides are oxidized by chlorine or oxygen, can also react with copper plumbing to cause corrosion and black water.

Typical finished water quality at Pickwick Park prior to installation of the aerator is shown in Table 8.2. When the aerators were installed, Mandarin Utilities instituted a comprehensive program for logging and investigating each consumer complaint. Before November 1980 (when Pickwick Park had no aerator), complaints of black-water corrosion numbered about 25 per month and were primarily confined to the Pickwick Park service area. The black-water problem at several residences served by Mandarin Utilities exhibited the classic symptom of black-water copper corrosion: a gritty, dark precipitate of copper sulfide, occurring predominantly on the hot-water side at the farthest point from the water heater.

Mandarin Utilities' managers determined that aeration to remove H_2S at Pickwick Park was necessary to solve the black-water problem. A cone-type aerator was installed between the wells and the ground-level storage tank at Pickwick Park. This additional treatment step effectively removed nearly all the dissolved sulfide from the finished water. Black-water complaints decreased from more than 25 to fewer than 5 per month in the 6 months following installation of the aerator.

However, a few customers continued to complain about persistent black-water problems. At this point, Mandarin Utilities hired an outside consultant to investigate the causes of the continuing problems and recommend corrective action.

Corrosion investigation and monitoring of the water supply procedure. Historical information such as complaint logs, plant operating data, and water quality data was evaluated to determine the cause and extent of the continuing corrosion problem.

Measured DO concentrations of between 3 and 6 mg/L throughout the Pickwick Park service area confirmed that the aerator was successfully eliminating sulfides from the treated water. An in situ test conducted to determine the extent of elemental sulfur present in the treated water indicated that less than 0.25 mg/L of colloidal sulfur was present. Particulate sulfur can accumulate in low-flow areas of a distribution system and cause localized corrosion problems, thus requiring continual vigilance. The amount of sulfur present in the Pickwick Park system during the test was too low to be a direct cause of black-water corrosion problems in the system.

Along with the elemental sulfur deposited on the filter, a small amount (0.04 mg/L) of oxidized iron was also present. This amount of iron oxide also would not be expected to cause problems in the system.

A finished water analysis was performed on 3 consecutive days. An LSI of -0.1 was calculated for these analyses, indicating that the water had a slightly corrosive tendency.

Table 8.2. Mandarin Utilities' finished water quality at Pickwick Park prior to aeration installation

TDS (mg/L)	452
Total hardness (mg/L as $CaCO_3$)	282
Alkalinity (mg/L as $CaCO_3$)	105
Calcium (mg/L)	61.8
Magnesium (mg/L)	30.8
pH, in situ	7.4
Iron (mg/L)	0.3
CO_2 (mg/L)	8.0
Temperature, in situ (°C)	25
H_2S (mg/L)	1.0
DO (mg/L)	None
LSI	−0.35

Source: Mandarin Utilities, 1981.

In addition, several residential connections that had been the source of numerous recurring complaints were visited by consulting engineers and utility personnel. One of the residences was found to have several galvanized-steel nipples coupled with copper elbows in the hot-water system. The galvanized nipples were removed and were found to be heavily tuberculated. Black copper-sulfide precipitate was found in the hot-water plumbing. The precipitate appeared to have accumulated over a long time in the crevices and tubercles caused by the iron corrosion. Other residences had similar galvanized connections on the hot-water side or on home water softeners preceding the water heaters. Most of the complaintants had not flushed their hot-water systems since the aerators were installed at Pickwick Park.

Results. Upon completion of the corrosion investigation conducted at residences with black-water problems, it was apparent that current complaints were due to a combination of improper plumbing practices (galvanic connections in household plumbing) and residual problems from the high sulfide water at Pickwick Park prior to installation of the aerator. Once copper corrosion is well established, corrosion products, which fill cracks, crevices, and tuberculated areas in pipes and water heaters, often set up "concentration cells." These cells continue to cause copper corrosion problems and can persist even in the original water quality problems are remedied. Accumulated copper sulfide tubercles can harbor bacteria which continue to corrode the copper plumbing. Even in the absence of continuing corrosion, residual corrosion products can take months or years to be completely eliminated because of the concentration cells or bacteria.

Recommended Control Methods

The following recommendations were proposed by the consulting engineers and are currently being implemented:

1. Add caustic soda (NaOH) to raise the pH by 0.3 to 0.5 unit to attain a positive LSI.
2. Baffle the storage tank outlet to obtain maximum use of the storage tank for settling of sulfur and iron particles and to reduce residual copper corrosion problems. (Although particulate elemental sulfur is not currently a major problem, sulfur accumulation in slow-moving sections of the system could compound residual copper corrosion problems.)
3. By-pass the aerator with part of the water to reduce the DO level to less than 1.0 mg/L. This water should be pumped directly into the clearwell so that it discharges below the water level into the storage tank to help reduce the DO of the finished water to acceptable levels.
4. Assist customers with residual copper corrosion problems through an aggressive program of repeated cleaning and flushing of household plumbing fixtures. Consider assisting residence owners with such corrective action by disconnecting water meters during major flushing efforts. Flushing with high chlorine residual water may be effective if bacterial action is adding to the residual copper corrosion. One or more test cases of flushing with high chlorine residuals should be attempted and the results monitored to determine the effectiveness of this remedy.
5. Continue the complaint response program, which involves inspection of galvanic connections at water heaters, water softener problems, and hot-water heaters and plumbing fixtures. Actions which the homeowner can take to reduce or eliminate residual copper corrosion (e.g., flushing, cleaning hot-water heaters and fixtures, or removing galvanic connections) should be identified at the time of inspection.

The engineers further advised the utility that residual corrosion problems at houses which have galvanic (copper to iron or steel) connections at water heaters are likely to resist correction until the galvanic connections are removed. Due to corrosion and tuberculation of the iron pipe or nipple, the rough surfaces provide, locations for residual copper corrosion to continue in spite of water quality improvement.

Mandarin Utilities currently is implementing the modifications suggested in recommendations 1 through 3 and has aggressively pursued recommendations 4 and 5, as well as the additional advice of the engineers, through an effective public information program, which has significantly reduced the number of corrosion-related complaints.

8.3 MIDDLESEX WATER COMPANY

This case history is excerpted from a publication by E.D. Mullen and J.A. Ritter, published in the May 1980 *AWWA Journal*, and it illustrates the following:

1. corrosion control by phosphate inhibitors;
2. a relationship between pH, temperature, inhibitor dose, and corrosion rate for a specific system; and
3. the use of coupon testing to evaluate several control strategies.

Background

Prior to 1969, MWC, located in Woodbridge, New Jersey, relied mainly on groundwater sources. To meet the growth in water demand, a new 20-MGD plant was built in 1969 to treat surface water from the Delaware and Raritan canals. Average water analyses for groundwater and surface water supplies are given in Table 8.3. More than half the MWC water distribution system consists of unlined cast iron mains. After the change from hard well water to soft surface water, MWC began receiving consumer complaints of discolored water in the areas where the iron mains were located. The discoloration was due to corrosion of the cast iron. Treating the surface water with caustic soda (NaOH) to obtain an LSI of +0.5 to +0.8 did not significantly reduce the red water complaints.

Table 8.3. Average water analyses

Chemical parameter	Surface water	Groundwater
Alkalinity (mg/L)	45	170
Hardness (mg/L)	68	260
DO (mg/L)	10	
Sulfate (mg/L)	49	83
Total solids (mg/L)	158	370
pH	7.7	7.7
Temperature (°C)	0.5–28	13

Source: Mullen and Ritter, 1980.

Initial Investigation and Monitoring Program

To monitor for corrosion and find a control method that would reduce customer complaints as well as protect the utility's mains and consumer's pipes, MWC initiated coupon (weight-loss) bench-scale laboratory studies. After contacting the ASTM and the NACE for information on coupon testing, MWC established a corrosion monitoring program according to NACE Standard TM-01-69.

MWC built two acrylic bench-test units, each consisting of three cylindrical cells connected in series, as shown in Fig. 8.3. The water entered through the inlet cell, which contained a control coupon. The center cell was the chemical-dosing cell, and the outlet cell contained the test coupon that measured the effects of chemical addition.

As discussed in Sect. 6.0, coupon tests measure the metal loss from corrosion over a specific time interval. The coupons are carefully weighed before and after they are placed in the water. Coupons are thoroughly cleaned of corrosion by-products and other foreign matter prior to being weighed. The difference in the coupon weights is the loss from corrosion, which can be converted into a corrosion rate by using the following formula:

$$\text{Corrosion rate}\,(mpy) = \frac{\text{weight loss}\,(mg) \times 534}{\text{area of coupon}\,(sq.\ in) \times \text{time}\,(h) \times \text{metal density}\,(g/cm^3)} \quad (16)$$

Testing of Alternative Control Methods

Alternative 1: Inhibitor treatment

Procedure. Initial bench-scale studies tested the effectiveness of adding two phosphate inhibitors to the pH-adjusted water.

Two milligrams per liter of a sodium-zinc-glass phosphate was added to one test unit, and 2.5 mg/L of ZOP was added to the second test unit. The test was conducted for 2 months.

Results. At the end of each month, the control and test coupons in each unit were weighed, and the corrosion rates were calculated from the measured weight losses. The bimetallic sodium-zinc-glass phosphate averaged a 13% reduction in corrosion rate. The ZOP averaged a 55% reduction in corrosion rate.

ORNL DWG 83-17048

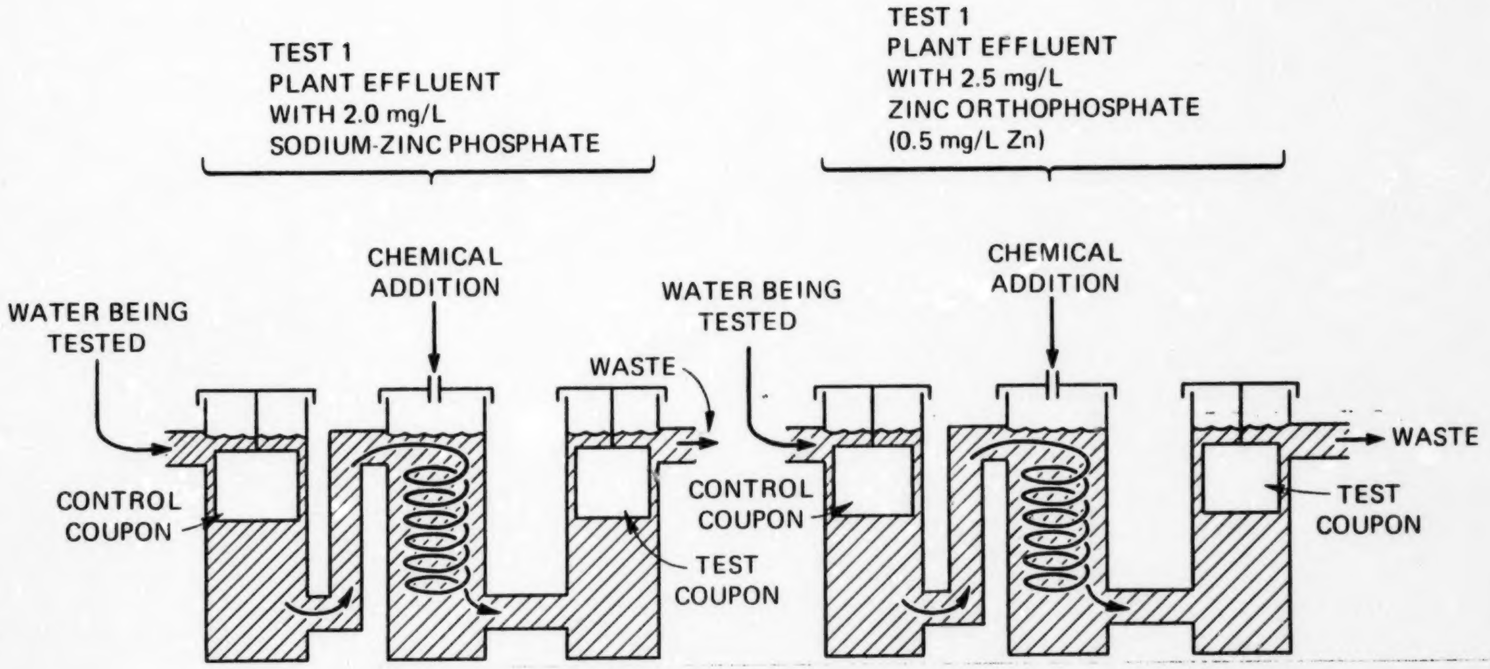

TEST 1
PLANT EFFLUENT
WITH 2.0 mg/L
SODIUM-ZINC PHOSPHATE
TEST 1
PLANT EFFLUENT
WITH 2.5 mg/L
ZINC ORTHOPHOSPHATE
(0.5 mg/L Zn)
CHEMICAL ADDITION
WATER BEING TESTED
WASTE
WATER BEING TESTED
CHEMICAL ADDITION
CONTROL COUPON
TEST COUPON
CONTROL COUPON
TEST COUPON
WASTE

Fig. 8.3. Coupon testing cell assembly.

Alternative 2: Addition of zinc orthophosphate with and without pH adjustment

Procedure. In these tests, 2.5 mg/L of ZOP (0.5 mg/L of zinc) was added to each of the two test units. Water in one unit was supplied by a line from the plant filter effluent (pH 6.8). Water in the other unit was supplied by plant effluent (pH 7.8). When the water temperature was higher than 18°C (65°F), the plant effluent was maintained at the pH of saturation, pH_s.

Results. Inhibitor treatment without pH adjustment reduced corrosion by 54%. Inhibitor treatment with pH adjustment reduced corrosion by 79%. During these tests, the following relationship between pH adjustment, inhibitor treatment, and temperature changes was discovered:

1. At temperatures below 13°C (55°F), inhibitor treatment without pH adjustment was more effective than inhibitor treatment with pH adjustment.
2. At higher temperatures, inhibitor treatment without pH adjustment increased corrosion.

Alternative 3: Testing of zinc orthophosphate addition and pH adjustment in the distribution system

Procedure. Coupons were placed at six locations in the distribution system. Monitoring started 5 months before the plant began inhibitor treatment. The liquid ZOP was stored in a 23-kL (6,000-gal) underground fiberglass tank. Chemical metering pumps inside the plant discharged to the clearwell reaction chamber. Capital investment totaled $11,500. A schematic of the inhibitor installation is shown in Fig. 8.4.

Results. Two areas were identified in which treatment could be improved to produce better water and reduce costs. It was found that during the winter, lower zinc dosages could be used, and the caustic soda pH adjustment could be reduced. Annual posttreatment caustic soda requirements have been reduced 60% from 15.2 mg/L in 1970 to 1971 to 6.1 mg/L in 1978. Peak corrosion rates (July and August) could be suppressed by increasing the zinc dosages, based on water temperature. The maximum summer zinc dosage needed in July was about 0.54 mg/L as zinc. In the cooler months, when the corrosion rate drops naturally as the water temperature drops, inhibitor treatment is continued at a lower dosage. The minimum wintertime zinc dosage is about 0.2 mg/L. MWC considered discontinuing the inhibitor treatment in the winter, but since the zinc phosphate film is constantly dissolving and being laid down, the film inhibitor treatment must be maintained.

In 1974, the six monthly distribution coupons were reduced to one monthly coupon. In 1975, MWC began the current program of measuring one coupon every 3 months. Inhibitor dosages and pH adjustments are increased or decreased with water temperature changes, which results in cost savings from lower corrosion rates and lower chemical costs. Between 1973 and 1978, corrosion rates were reduced by about 70 to 80%.

8.4 SMALL HOSPITAL SYSTEM

This study, conducted by a private consultant, illustrates an economical, low maintenance solution to copper corrosion in a small system.

Background

Prior to the opening of a small 15-bed hospital in the eastern Sierra Nevada Mountains of California, blue staining from copper was apparent in every water fixture. Chemical analyses showed up to 10 mg/L of copper in the water. The corrosion appeared to be general or uniform, without evidence of pitting. The water supply to the hospital is surface lake water, containing 20 to 40 mg/L total dissolved solids (TDS) at about pH 6. The LSI of the water averages -2.0.

Initial Investigation and Monitoring Program

Procedure. The task was to make the water less aggressive by adjusting the pH. Mechanical feeders could not be used to adjust the pH because they are not accurate or reliable at low-flow rates.

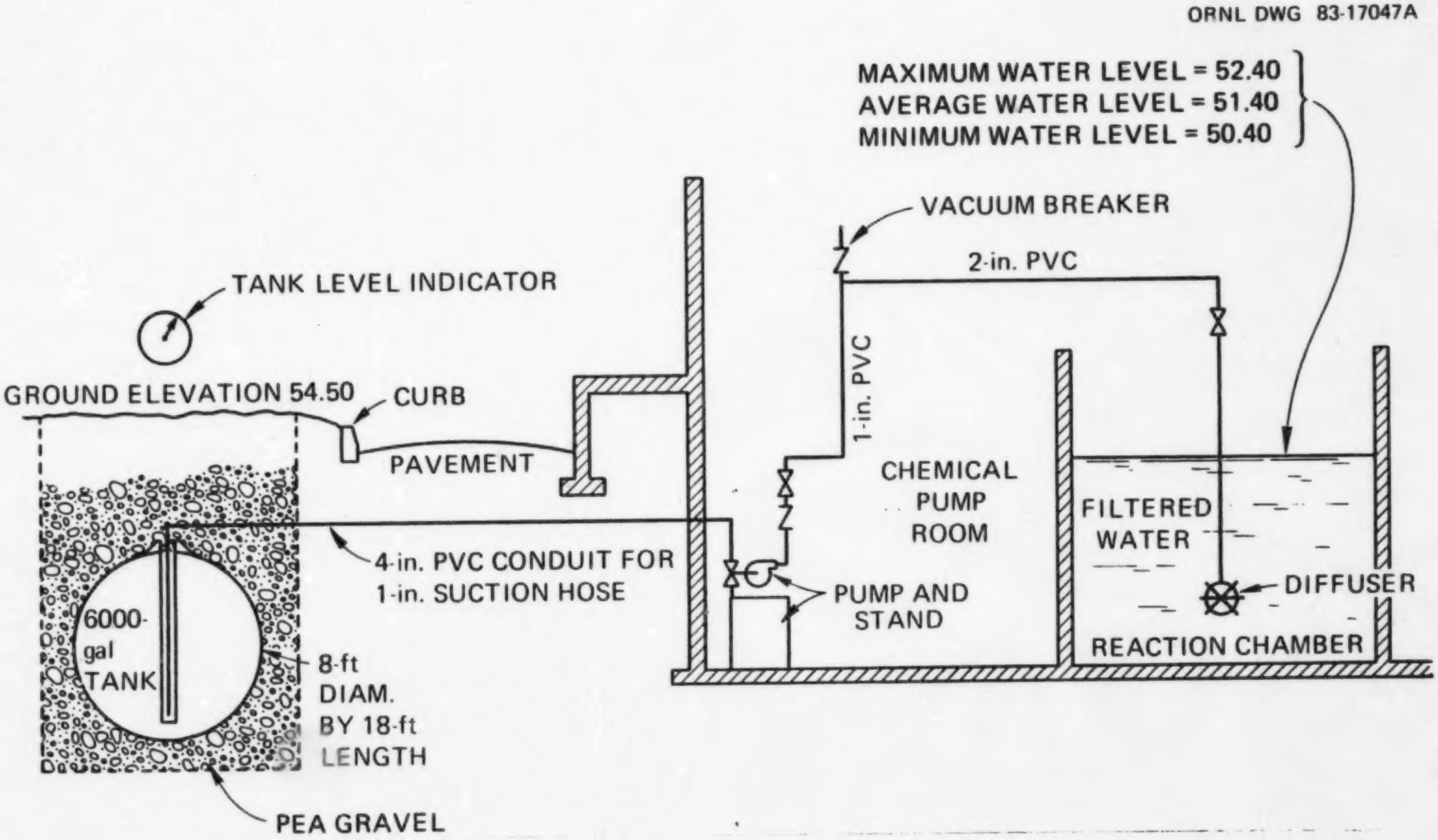

ORNL DWG 83-17047A
MAXIMUM WATER LEVEL = 52.40
AVERAGE WATER LEVEL = 51.40
MINIMUM WATER LEVEL = 50.40
VACUUM BREAKER
2-in. PVC
1-in. PVC
TANK LEVEL INDICATOR
GROUND ELEVATION 54.50
CURB
PAVEMENT
CHEMICAL PUMP ROOM
FILTERED WATER
DIFFUSER
REACTION CHAMBER
PUMP AND STAND
4-in. PVC CONDUIT FOR 1-in. SUCTION HOSE
6000-gal TANK
8-ft DIAM. BY 18-ft LENGTH
PEA GRAVEL

Fig. 8.4. Schematic of inhibitor installation.

To solve the copper corrosion problem, a 5-ft × 24-in. tank was installed on the incoming-water line. The tank was filled with crushed calcite ($CaCO_3$), approximately ⅜ in. in diameter. Empty bed contact time at maximum flow was about 5 min.

Results. The water picked up about 4 to 6 mg/L of calcium while in contact with the limestone. Alkalinity increased by 10 to 15 mg/L, and the pH rose to about 7.2. The water became less aggressive, and the staining stopped. The system contains no moving parts and requires no maintenance other than the addition of calcite about once a year.

8.5 BOSTON METROPOLITAN AREA WATER SYSTEM

This case history, excerpted from a paper presented by P.C. Karalekas, C.R. Ryan, and F.B. Taylor at the 1982 AWWA Miami Conference illustrates the following:

1. the problems associated with lead corrosion in an old distribution system containing lead piping,
2. the effects of phosphate inhibitor and pH control programs on lead corrosion rates, and
3. the benefits of a good monitoring program for evaluating corrosion control methods.

Background

Studies prior to that by Karalekas et al. had shown that lead concentrations at customer's taps in the Boston metropolitan area were consistently above the NIPDWR acceptable level (0.5 mg/L).

Boston and the surrounding communities purchase water wholesale from the Metropolitan District Commission (MDC), a state agency. The MDC pipes water from Quabbin Reservoir to the Wachusett Reservoir and then to the metropolitan area. The watersheds of these two large reservoirs are well protected from pollution sources.

The MDC serves about 1.8 million people in the entire Boston metropolitan area, having an average daily demand of about 300 MGD.

Prior to the start of corrosion control, treatment consisted of only chlorination and ammoniation. Table 8.4 lists various raw and finished water quality parameters. Raw water is low in hardness, alkalinity, TDS, and pH, all of which indicate soft corrosive water. Copper, iron, zinc, and lead are consistently below detection limits in both raw and finished water. Finished water represents water after treatment with chlorine, ammonia, hydorfluosilicic acid, and NaOH. The major difference between raw and finished water is the increase in pH from 6.7 to 8.5. Alkalinity and sodium also increase.

Lead in Boston water results from a combination of a soft corrosive water, which is quite acidic and low in hardness and alkalinity, and the extensive use in the past of lead pipe for service lines and plumbing.

In a 1975 study conducted in the Boston metropolitan area, Karalekas et al. found 15.4% of the water samples collected at consumer's taps exceeded the lead standard. Furthermore, more than 70% of the 383 homes surveyed had detectable levels of lead in their drinking water, which indicated the widespread nature and seriousness of the problem.

Finding high lead concentrations from the corrosion of lead pipe and the association between lead in water and blood prompted the MDC to embark on a treatment program to protect public health by reducing corrosion.

Initial Investigations and Monitoring

Procedure. Before the MDC began treating their water to reduce corrosion, EPA developed a monitoring program which involved sampling for trace metals at consumer's taps known to be supplied through lead service lines. The purpose of this sampling program was to evaluate water quality both prior to and after implementing corrosion control. This sampling has been done regularly since 1976. At the outset, 23 homes with lead service lines were included in the sampling. During

Table 8.4. Metropolitan District Commission water quality data

Parameters	Shaft 4 (Southborough, MA) Raw water	Norumbega Reservoir (Weston, MA) Finished water
Hardness (as $CaCO_3$)	12	12
Alkalinity (as $CaCO_3$)	8	12
TDS	37	46
Calcium	3.2	3.4
Sodium	5.5	9.7
Sulfate	<15	<15
Chloride	<10	<10
Specific conductance (micromhos)	59	78
pH (units)	6.7	8.5
Copper	<0.02	<0.02
Iron	<0.10	<0.10
Zinc	<0.02	<0.02
Lead	<0.005	<0.005

All values in mg/L unless otherwise specified.

the intervening period, a number have been dropped or have missed months because the occupants moved. Currently, 14 of the original 23 homes are being monitored.

To assess the variation in lead concentration in drinking water that had been standing for varying lengths of time in piping, three samples were collected at each home, by the homeowner, using the instructions in Table 8.5. Water was collected at the kitchen sink the first thing in the morning, before any water was used in the house.

Sample 1, the interior plumbing sample, was collected immediately upon opening the faucet. This sample represented water that had been standing overnight in the fixture and the interior plumbing serving the faucet. Sample 2, the service line sample, was collected after the sample collector felt the water temperature change from warm to cold. Since water would be expected to warm slightly after standing in interior plumbing, this cold water would represent water that had been standing overnight just outside the foundation of the house and in contact with the interior of the lead service line underground. Sample 3, the water main sample, was collected after allowing the water to run for several minutes. This sample represented water that would have a minimum contact with the service line and the interior plumbing.

Results. Monitoring results showed that lead concentrations at the customer's taps were consistently well above the NIPDWR level of 0.05 mg/L.

Testing of Alternative Control Methods

Because lead pipe was used extensively throughout the system, its removal would have been prohibitively expensive and consequently was not a feasible option. Therefore, two alternative methods of controlling lead corrosion were implemented and evaluated between 1976 and 1981.

Table 8.5. Sampling instructions

After 11:00 p.m., do not use the kitchen cold water faucet until collecting the water samples the next morning. Using the following directions, in the morning, collect the water samples at the faucet before using any faucet or flushing any toilets in the house. Fill the provided containers to 1 inch below the top and put the caps on tightly.

Sample 1:	Open the cold water faucet, immediately fill bottle #1, and turn off the water. Recap this bottle.
Sample 2:	Turn the faucet on and place your hand under the running water, and immediately upon noticing that the water turns colder, fill bottle #2. Recap this bottle.
Sample 3:	Allow the water to run for 3 additional minutes and then fill bottle #3. Recap this bottle.

The representative from EPA will stop at your house on the morning of ______________, to pick up the samples. If you do not expect to be home, please leave the samples outside the front door.

Alternative 1: Treatment with ZOP

Procedure. In June 1976, MDC began treating the water with ZOP, a commercial corrosion inhibitor. ZOP was tried because of its reported effectiveness in controlling iron corrosion and its potential for controlling lead corrosion. After an initial ZOP dose of about 13 mg/L for several weeks, the dosage was reduced to between 3.2 and 4.5 mg/L for the remainder of the trial, which ended in December 1976.

Results. Figure 8.5 illustrates the variation in lead concentrations over time for all lead samples collected from February 1976 to mid 1981. Each point represents the average of 39 to 69 separate samples collected in the distribution system.

As can be seen from the graph, the average lead concentration was consistently above 0.05 mg/L between February 1976 and May 1977. During the period in which ZOP was used, there appeared to be an initial increase in lead followed by a subsequent decrease. This may have been due to adding the ZOP or to some other factor, such as water temperature. In Fig. 8.6, which plots water temperature versus time, a close parallel between temperature and lead can be noted. Water temperature increases in the summer months appear to be followed by increases in lead, and water temperature decreases appear to be closely followed by decreases in lead. It should be noted that there is more than a 30°F seasonal change in water temperature, which can certainly account for part of the change because of the resulting increase in chemical reaction rates and, thus, the increased corrosion potential. Whatever the reason for the fluctuation in lead, it is clear that lead concentrations were not reduced to below the standard by the inhibitor. Because of this fact and problems of algal growth in distribution storage reservoirs, which may have been associated with phosphate addition, the use of ZOP was discontinued.

Alternative 2: pH adjustment with NaOH

Procedure. There was a 6-month interval between the time ZOP use was stopped and pH adjustment was initiated. In May 1977, MDC began adding NaOH to raise the pH to levels between 8 and 9, as shown in Fig. 8.5.

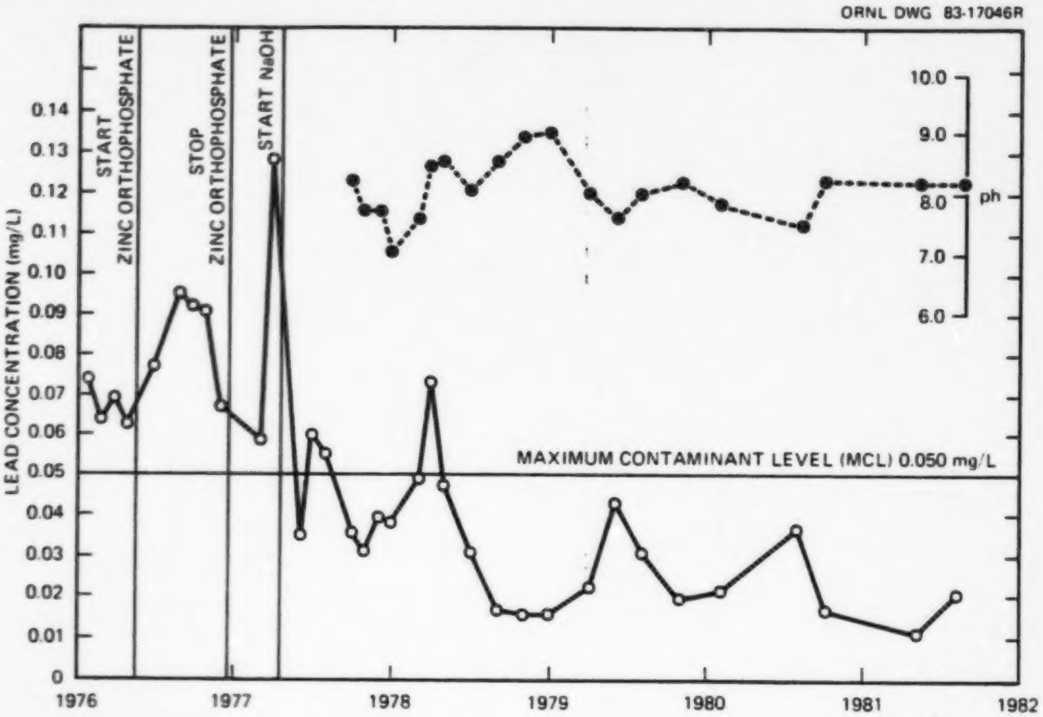


Fig. 8.5. Mean lead levels from samples taken in Boston and Sommerville, Massachusetts, 1976-1981.

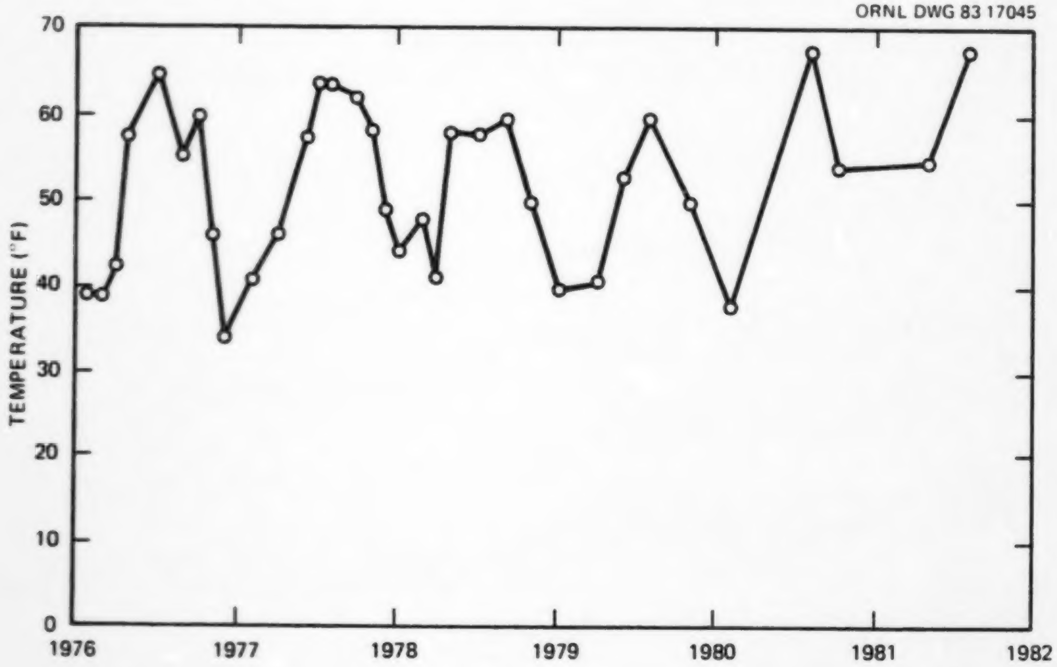


Fig. 8.6. Water temperature, Metropolitan District Commission, Norumbega Reservoir.

Results. As Fig. 8.5 illustrates, using NaOH to adjust pH levels resulted in substantially reduced lead concentrations. There were two brief periods in which average lead concentrations were above 0.05 mg/L due to interruptions in pH adjustment. The first occurred when an underground NaOH line froze during the winter of 1978 because a pump malfunctioned, and the second occurred when a building was struck by lighting in the summer of 1977.

In 1979, a close relationship between average pH values and average lead concentrations, as determined from samples taken at the consumers' taps was observed. From January to June, when the pH dropped from 9 to less than 8, there was a concurrent rise in lead concentrations. From June to December, pH levels increased to more than 8, and drop in lead concentration was observed, leading to the conclusion that there was a causal relationship between pH levels and lead concentrations (i.e., as the pH increased, lead decreased).

Figure 8.7 shows the variation in copper concentrations during the same period of 1976 through 1981. Prior to corrosion control, average copper concentrations ranged as high as 0.35 mg/L, still below the recommended level of 1.0 mg/L. Again, a significant reduction is seen in copper levels after the adjustment of pH using NaOH. Currently, copper concentrations average about 0.05 mg/L.

Figure 8.8 represents average iron concentrations over time. While there is not the dramatic decrease in iron that was seen in copper and lead, note that iron concentrations are at their lowest levels in 5 years. There has been an apparent, gradually downward trend during the past several years, which indicates that pH adjustment has had a positive effect on controlling iron corrosion. With less fluctuation in pH from 1979 to 1981, as compared with previous years, there is apparently less fluctuation in iron concentrations, again with a downward trend.

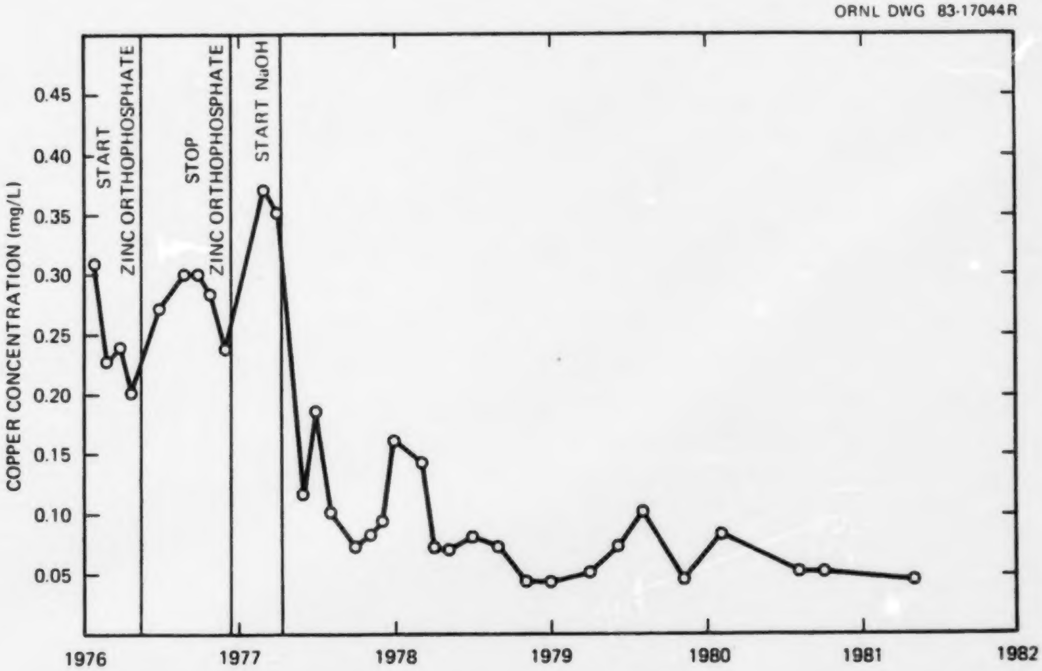


Fig. 8.7. Mean copper levels from samples taken in Boston and Sommerville, Massachusetts, 1976-1981.

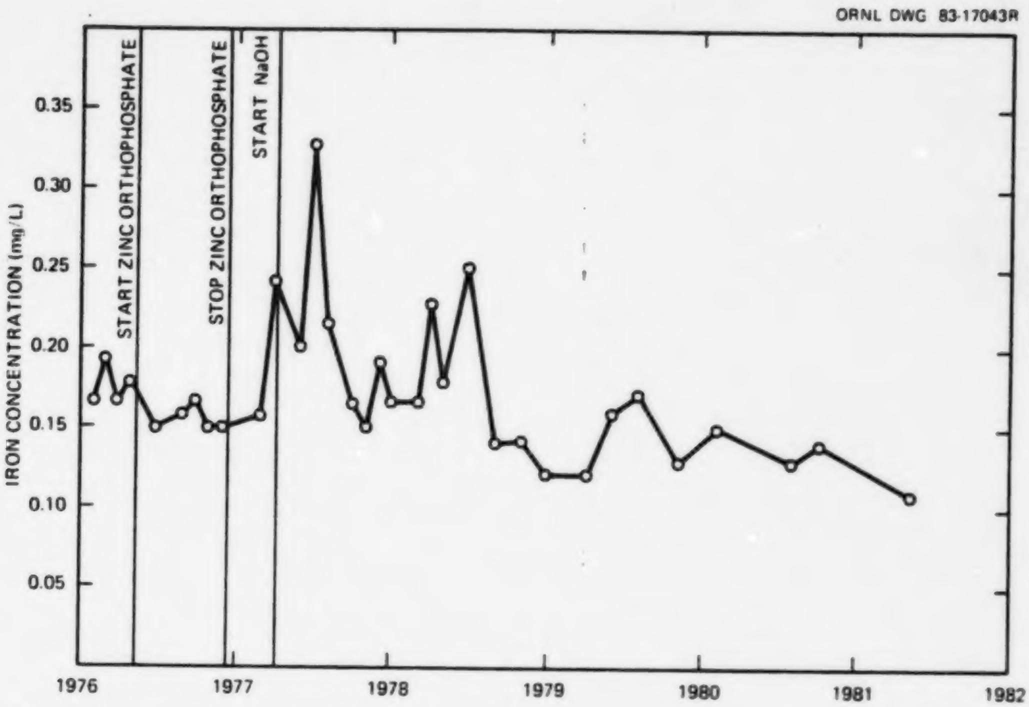


Fig. 8.8. Mean iron levels from samples taken in Boston and Sommerville, Massachusetts, 1976-1981.

Summary and Conclusions

At present, MDC is adding 14 mg/L of 50% NaOH to treat an average daily demand of 301 MGD. Chemical costs for NaOH were $900,000 in 1981, with operating and maintenance expenses of $161,000 for that year. The cost per million gallons treated is $9.64. MDC serves approximately 1,800,000 people in the Boston metropolitan area, which would give a cost per person per year of $0.59.

To summarize, this study shows that pH adjustment using NaOH has effectively reduced both lead and copper corrosion in the Boston area and that a monitoring program is essential to evaluating any proposed corrosion control scheme.

8.6 GALVANIZED PIPE AND THE EFFECTS OF COPPER

This case history differs from the others presented here in that it its not actually one case history but is a composite of incidents from consulting experiences. It is included to illustrate the effects of copper on galvanized pipe and to offer possible remedies.

Background

The waters in these cases were not severely corrosive. None of the waters involved, however, was capable of laying down a protective scale in cold weather. The copper in several of the systems resulted from efforts to control algae in surface water supplies using copper sulfate. The literature reports that concentrations as low as 0.01 mg/L can potentially cause problems.

The corrosion mechanism is as follows: Copper, upon entering a galvanized system, will plate out on the zinc surface. Copper, being the more noble or inactive metal, then becomes the cathode. The zinc (or steel) becomes the anode and goes into solution. This type of problem usually is accompanied by severe tuberculation inside the pipe. Under each tubercle is a pit. In severe cases, the pitting leads to perforation and failure of the pipe.

This problem is not confined to copper that comes in with the water. Hotels, apartments, and some commercial buildings frequently have a central heater which continuously recirculates hot water. Frequently, the heat exchange surfaces (heater coils) are copper, and the plumbing system is galvanized. The problem is the same as described previously.

Possible Remedies

If traces of copper in the water are known or suspected, the builder should use a material other than galvanized pipe in the plumbing system. If that is not possible, the system must be protected *from the outset* by a "scavenger pot." This device is simply a flow-through container which is mounted on the incoming line and provides at least a 1-min empty bed detention time. The unit is charged with a metal higher in the galvanic series than copper so that the copper will plate out on the metal in the scavenger pot and not enter the system. Mossy zinc and magnesium have been used successfully.

In existing systems suffering from this problem, installing a scavenger pot will not cure the problem because the copper is already deposited in the lines. It will merely prevent more copper from aggravating the situation. In such systems, the use of polyphosphate inhibitors has, at times, helped in stifling the cathode reaction. However, caution should be used because if the system is severely tuberculated, the polyphosphate may initially react preferentially with existing corrosion products, resulting in leaks from areas in the system that are severely corroded. These leaks usually manifest themselves within 10 days to 2 weeks after initiation of treatment.

8.7 GREENWOOD, SOUTH CAROLINA

This study, which illustrates the effect of adding ZOP to control corrosion in A-C pipe, was conducted by the CPW, Greenwood, South Carolina, under the sponsorship of EPA. A more detailed account of this study can be found in the EPA report titled "Field Test of Corrosion Control to Protect Asbestos-Cement Pipe" (Grubb 1979).

Background

The water distribution system in Greenwood, South Carolina, contains a great deal of A-C pipe, most of which was installed in the late 1940s and the early 1950s.

The water source for Greenwood is surface water from Lake Greenwood. Prior to this study, treatment consisted of alum coagulation, sedimentation, filtration, pH adjustment with NaOH, and chlorination. Water quality values for raw and finished water are given in Table 8.6. The finished water had an AI of about 10.4 to 10.5, which is considered moderately aggressive.

Table 8.6. Greenwood, South Carolina water quality data

Parameter	Raw water	Finished water
pH, pH units	Variable	8.2–8.3
Alkalinity, mg/L	15	20
Total hardness, mg/L as $CaCO_3$	10	10
Iron, mg/L	0.4	0.1
Free chlorine residual	None	0.75

Initial Investigation and Monitoring Program

At the request of the CPW, EPA tested several Greenwood samples for asbestos fibers. The results of the testing confirmed the presence of asbestos fibers in the water and led the Commissioners to participate in a project to determine whether a chemical could be fed into the water system to coat the pipe sufficiently to prevent further corrosion of the cement and asbestos fibers.

Initial sampling showed that the pH of the water increased as the water passed through the distribution system. Many of the larger mains are concrete or cement-lined pipe, which caused an increase in pH before the water reached the A-C pipe in the system. However, the increase in pH was not sufficient to stabilize the water, and the pH continued to rise when it contacted the A-C pipe.

This study was the first of its type concerned with A-C pipe. At the time this study was started, the apparent corrosion of A-C pipe in use was evaluated almost entirely by electron microscope asbestos fiber counts on water samples from the system. It was later learned that fiber counts can be significantly increased, albeit temporarily, by drilling and tapping the pipe. These temporary increases in asbestos counts can lead to a false evaluation of the general condition of the pipe.

Testing of Control Method

Procedure. Prior to testing, A-C pipe was installed at the two test sites, known as Effie Drive and Canterbury, with a 15-cm (6-in.) section being installed at Effie Drive under low-flow conditions, and a 20-cm (8-in.) section at Canterbury under high-flow conditions.

ZOP was introduced into the system on October 11, 1977, at a feed rate of 3.0 mg/L. The passivation period was terminated on October 14, 1977, short of the intended date of October 15, because of problems encountered by one of the system's largest users, a pharmaceutical company. This firm processes gauze and surgical supplies and used a cotton-filament-wound filter to remove rust or iron particles as well as other particles in the water. The high concentrations of ZOP clogged the filters sufficiently to cause serious problems. The company had to change filters every 2 to 3 days during the initial periods, whereas normally a set of filters would have lasted 6 to 7 months. The feed rate was reduced to 0.5 mg/L in an effort to ease filter problems. Zinc was found at 0.17 mg/L at Effie Drive, the low-flow location, and it was therefore concluded that zinc was present throughout the system.

The problems continued with the filters at the pharmaceutical company, however, and on November 11, 1977, the zinc feed rate was lowered to 0.3 mg/L, resulting in a decrease in the concentration of zinc at the Effie Drive location to less than 0.1 mg/L. This rate was continued until the end of the study, although problems were still encountered with the company's filters.

Samples of water were routinely taken from two locations where A-C pipe was used. Samples were checked for zinc content, pH, alkalinity, and calcium as $CaCO_3$.

Water samples were also forwarded to the EPA laboratory in Cincinnati to determine the number of asbestos fibers present. The two pipe sections were removed and examined for the amount of zinc deposited on their surfaces.

Results. Routine tests, such as pH and alkalinity, showed no significant changes in these parameters during the study period. The AI of the water at the closer, high-flow location ranged from 10.6 to 11.2. At the more distant, low-flow location, the AI varied from 11.2 to 11.9—a range considerably higher than the 10.4 to 10.5 AI values at the treatment plant.

After the initial passivation period, zinc concentration at the closer sampling location averaged about 0.2 mg/L; at the distant location, it was generally less than 0.2 mg/L, averaging 0.1 mg/L. These concentrations were not sufficient to prevent a rise in pH and calcium between the two sampling locations. Most of the calcium increase in the distribution system occurred between these sites, where zinc concentration was lowest.

Two times after A-C pipe had been tapped in the sampling location vicinity, high asbestos fiber counts were observed. Because, as was stated earlier in this section, pipe tapping operations can temporarily raise the fiber count in the distribution system, the use of tapping machines equipped to flush away drilling and tapping debris is recommended.

Electron microscope photographs and energy dispersive X-ray spectra analyses showed coatings of zinc products on the two pipe samples.

The scanning electron microscope (SEM) was used to examine the interior pipe wall of pipe samples removed from both sampling locations. The interior surface of the 20-cm (8-in.) pipe was smooth, and some coating resulting from zinc treatment could be identified. The interior of the 15-cm (6-in.) pipe, used with a lower concentration of zinc (0.1 mg/L), had much larger uncoated areas on the pipe surface.

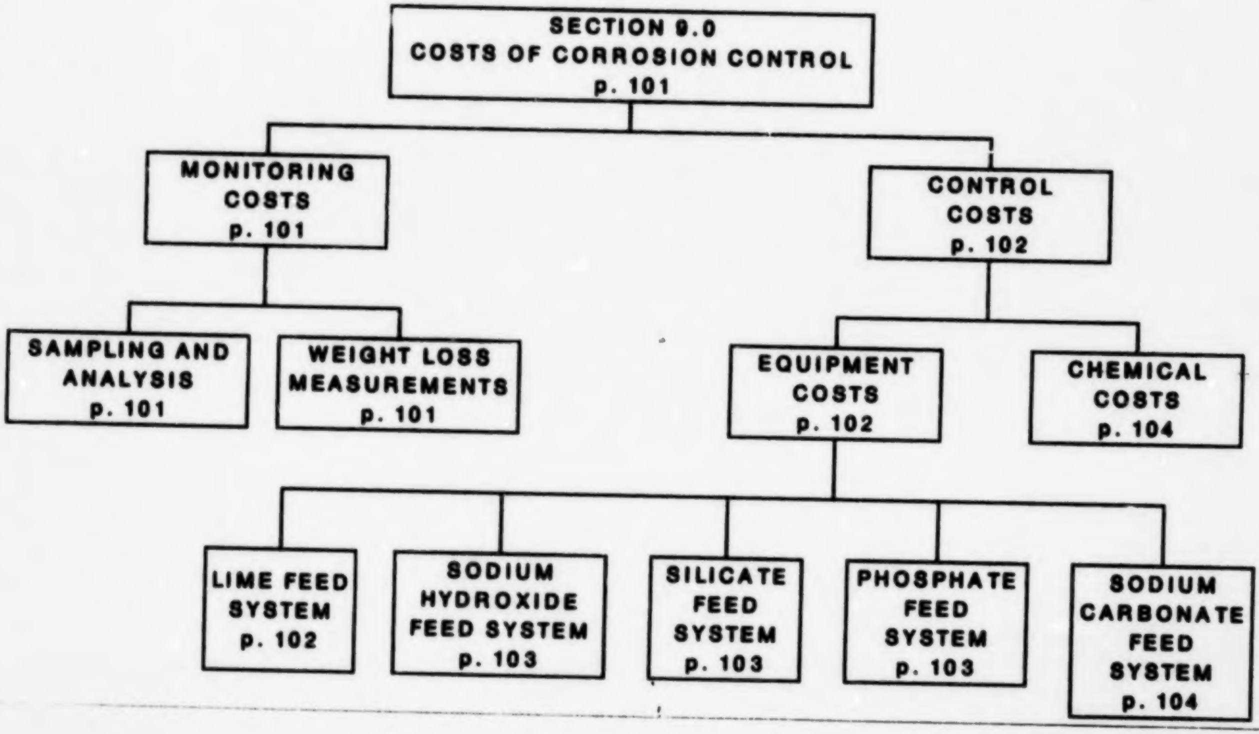
Regardless of which portion of the pipe was examined, the 20-cm (8-in.) pipe always showed better coverage than the 15-cm (6-in.) pipe. This indicates that the zinc or zinc compounds do adhere to the A-C pipe, and that to be effective, the zinc concentration should be 0.2 mg/L, or higher if possible.

Because zinc precipitates in the system, the amount of ZOP dosed at the treatment plant to obtain the desired zinc residual would have to be determined for each system.

The report concluded that the release of asbestos fibers from A-C pipe can be reduced by maintaining a zinc coating on the pipe material by adding ZOP.

ORNL-DWG 83C-18351

INDEX TO SECTION 9


SECTION 9.0
COSTS OF CORROSION CONTROL
p. 101
MONITORING COSTS p. 101
CONTROL COSTS p. 102
SAMPLING AND ANALYSIS p. 101
WEIGHT LOSS MEASUREMENTS p. 101
EQUIPMENT COSTS p. 102
CHEMICAL COSTS p. 104
LIME FEED SYSTEM p. 102
SODIUM HYDROXIDE FEED SYSTEM p. 103
SILICATE FEED SYSTEM p. 103
PHOSPHATE FEED SYSTEM p. 103
SODIUM CARBONATE FEED SYSTEM p. 104

9.0 COSTS OF CORROSION CONTROL

This section outlines costs associated with some common corrosion control procedures. Costs are presented for sampling and analysis, rate measurement tests, and various types of equipment and chemicals used in corrosion control. The costs may vary considerably among utilities of different sizes and in different regions of the country and should not be used by any individual utility to estimate the cost of a specific corrosion control program. The data presented here are useful, however, for comparing costs of alternative corrosion control methods.

9.1 MONITORING COSTS

Sampling and Analysis

Sampling and analytical costs to monitor and control corrosion will vary among utilities, depending on the number of parameters analyzed, the number of samples collected, the type of materials used in the system, and the type of control program being monitored by the utility.

To comply with the 1980 NIPDWR amendments, only one or two (if the surface water supplies are used) samples for the following parameters are required:

1. alkalinity, milligrams per liter (mg/L) as calcium carbonate ($CaCO_3$);
2. pH, as pH units;
3. hardness, mg/L as $CaCO_3$;
4. temperature, °C or °F; and
5. TDS, mg/L.

The cost of conducting these analyses is minimal and ranges from less than $20 to $75, depending on whether the utility performs an in-house analysis or sends the samples to an outside laboratory.

Additional sampling and analysis are required to determine if corrosion is occuring and what materials are being corroded, as discussed in Sect. 6.0. Table 9.1 presents typical costs of analyzing several water quality parameters which affect corrosion rates. Analyzing the samples in-house whenever possible can result in cost savings.

Weight-Loss Measurements

The main costs of coupon or weight-loss methods are

1. the initial purchase and installation of the coupons;
2. labor costs of setting up the test;
3. dismantling and weighing the coupons after a specified time period;
4. the cost of any water quality modifications tested during the test period (such as pH adjustment, reduction of oxygen, pipe lining, or inhibitor treatment).

The costs vary depending on the number of coupons placed in the system, the number of different materials tested, and whether the utility performs the study in-house or hires an outside consultant to conduct the tests. Middlesex Water Company, which conducted in-house weight-loss measurements, reported in 1980 that the cost of their monitoring program is currently about $15 per coupon, excluding chemical costs. A more detailed description of the Middlesex monitoring program is given in Sect. 8.3, Case Histories.

Preceding page blank

Table 9.1. Cost of typical analytical services for drinking water (1982)

Primary standards		Secondary standards		General	
Parameter	Cost	Parameter	Cost	Parameter	Cost
Arsenic (As)	10	Chloride (Cl)	14	Total hardness ($CaCO_3$)	14
Barium (Ba)	10	Color	10	Total alkalinity ($CaCO_3$)	14
Cadmium (Cd)	10	Copper (Cu)	10	N.C.H. ($CaCO_3$)	2
Chromium (Cr)	10	Corrosivity	45	Bicarbonate (HCO_3)	2
Lead (Pb)	10	Foam Agents (MBAS)	25	Calcium (Ca)	10
Mercury (Hg)	25	Iron (Fe)	10	Magnesium (Mg)	10
Selenium (Se)	10	Maganese (Mn)	10	Carbon dioxide (CO_2)	2
Silver (Ag)	10	Odor	35	Bicarbonate ($CaCO_3$)	2
Nitrate (N)	24	pH	10	Carbonate ($CaCO_3$)	2
Fluoride (F)	14	Sulfate (SO_4)	17	Hydroxide ($CaCO_3$)	2
Turbidity (NTU)	10	Sodium	10	pH, index	2
	143	TDS	17	RSI	2
		Zinc (Zn)	10	LSI	2
Pesticides	250			H_2S	20
Endrin					
Lindane					
Methoxychlor					
Toxaphene					
2,4–D					
2,4–5 Silvex					
Total cost	393		233		86

Costs given in 1982 dollars.

9.2 CONTROL COSTS

The equipment and chemical costs presented in this section are approximate costs for the purpose of making comparisons. Equipment costs will vary depending on size, quality, features, and construction materials. In addition, many site-specific factors will affect the total system costs. These factors include labor costs, quantity of piping and valves needed, construction materials, housing requirements, bulk storage, unloading/conveyance systems, and site preparation needed.

Chemical costs for water quality modification will vary with location, transportation costs, and volume of chemicals purchased. Water utility personnel are advised in all cases to contact water treatment chemical and equipment suppliers in their areas to determine actual costs of an in-place control system.

9.2.1 Equipment Costs

Lime Feed System Costs. Small lime feed systems [<40 to 50 pounds per hour (lb/h)] usually feed hydrated lime [$CA(OH)_2$], purchased in 100-lb bags. These feed systems generally consist of a storage hopper supplied with a volumetric or gravimetric feeder. The feeder transfers the lime to a dissolving or slurry tank. The lime slurry is then pumped to the point of application by a metering pump.

Larger systems usually feed quicklime, CaO, and require a lime slaker to hydrate the lime and produce a lime slurry. The lime slurry is pumped, or flows by gravity, from the slaker to the point of application.

For stabilization, a lime dose of about 10 mg/L is often adequate. Cost estimates for lime feed systems for several plant sizes are given below. The costs are for equipment sized to feed a dose of 10 mg/L.*

---

* Updated costs based on costs presented in Environmental Protection Agency publication "Estimating Water Treatment Costs," Vol. 2. By Culp/Wesner/Culp; August 1979.

Plant size[a]	Capital cost[b]	Annual maintenance cost[c]
3 MGD	$20,000	$ 4,000
30 MGD	$75,000	$15,000

[a] MGD = million gallons per day.

[b] Includes manufactured equipment (slaker, storage hopper, bins, pumps, etc.), labor, piping valves, and electrical instrumentation. Housing, bulk storage, and unloading/conveyance system costs are not included.

[c] Includes operation and maintenance labor and electrical power costs.

Sodium hydroxide feed systems. Small systems (<200 lb/d)which feed NaOH generally use dry NaOH. The dry NaOH is delivered in drums and then mixed manually or with a volumetric dry feeder to a 10% solution onsite and is fed with a metering pump. The cost for a small system (1 to 2 MGD) equipped with a volumetric feeder, storage hopper, feed/mixing tank with mixer, and metering pump, including heated indoor storage and appropriate piping and valves, would be approximately $17,000 to $20,000.

For larger systems, NaOH is generally purchased as a 50% liquid solution, containing 6.4 lb of NaOH per gallon. Because 50% liquid NaOH begins to crystallize at 54°F, bulk storage facilities for NaOH must either be located in a heated building or have heating coils in the storage tank. The total capital cost for a bulk liquid NaOH feed system suitable for a 50-MGD plant would be $60,000 to $65,000 (based on updated costs from the EPA report "Estimating Water Treatment Costs," (EPA 1979). This includes the cost of indoor bulk storage tanks having fiber-glass-reinforced polyester housing, metering pumps, flow monitoring equipment, electrical instrumentation, piping and valves, and installation labor.

Silicate feed systems. Although sodium silicate is a white powder, it is usually marketed as an opaque solution in 50-gal drums or tank cars.

Many small systems often feed sodium silicate directly from the shipping container to the point of application using a metering pump and polyvinyl chloride (PVC) piping. Larger systems use a bulk storage tank and feed the silicate to the point of application through PVC piping using a metering pump.

The cost for a silicate feed system for a less than 3-MGD plant is approximately $1,000 to $1,300. This cost includes a metering pump to feed directly from the shipping drum to the point of application plus associated PVC piping and valves. For a larger system (50-MGD), feeding from a bulk storage facility, the cost would be in the range of $15,000 to $20,000. This includes the cost of bulk storage, a metering pump, PVC piping, installation labor, and electrical instrumentation.

Phosphate feed systems. Phosphate compounds for corrosion control are available in liquid form but are commonly bought and shipped as dry solids. In systems handling less than 10 MGD, the dry phosphate compound is usually put into solution in a dry tank and fed with a chemical metering pump. In systems larger than about 10 MGD, a gravimetric or volumetric feeder which transfers the dry material to a dissolving tank is usually required. A chemical metering pump is used to feed the solution from the tank or from an additional dry tank.

The cost of a phosphate feed system for plants handling up to about 10 MGD using two feed tanks—one equipped with a mixer and dissolving tray—plus a chemical metering pump, PVC piping, valves, and flow meter, is in the range of $1,500 to $2,000.

For larger systems which use a dry-solids feeder and loading hopper in addition to the feed tanks the cost is approximately $12,000 to $15,000. This also includes the cost of a metering pump, PVC piping, valves, installation labor, and flow meter.

Operation and maintenance costs for these systems are moderate. The major cost for both systems is the phosphate. For smaller systems, an operator must periodically prepare a batch of feed solution. This may occur once or several times per day, depending on the system size. Electrical costs are negligible due to the small motor sizes used in the mixer and the metering pump.

Operation requirements for larger systems include periodically charging the hopper with dry phosphate, equipment maintenance, and monitoring. Power costs with the larger systems are more but are still negligible.

Sodium carbonate feed system. Sodium carbonate is sold as a dry white powder in bags or barrels or in bulk (i.e., carloads and truckloads). Its solubility varies with temperature. At 68°F, its solubility is 1.5 lb/gal; at 86°F, its solubility is 2.3 lb/gal. Small systems can feed sodium carbonate by manually making up batch solutions in dissolving tanks and feeding the solution with a metering pump. The cost for a small system such as this, including the tank, metering pump, flow meter, associated PVC piping, valves, and installation labor would be approximately $1,500 to $2,000.

A larger system would require the use of a gravimetric or volumetric feeder to feed the material from a storage hopper into the dissolving tank. Because the material tends to adhere to the sides of the bin, arch, and flood, a hopper agitator is required for the light and powdery grades.

A system of this type for a larger plant (50 MGD) would cost in the range of $12,000 to $15,000, including a vibrator-equipped storage hopper, volumetric feeder, dissolving tank, metering pump, PVC piping, valves, flow meter, and installation labor.

Chemical Costs

Chemical costs for the most common chemicals used in corrosion control are given in Table 9.2. These costs can vary considerably depending on the size and location of the plant, the time of year, and the particular chemical supplier. The costs are not intended to represent actual costs to a utility. Each utility is advised to contact local chemical suppliers to determine the costs for a specific plant. The figures do, however, indicate a cost range which can be useful in considering alternative corrective actions for corrosion control.

Table 9.2. Typical annual chemical costs for corrosion control (1982)
Costs do not include freight

Chemical	Use	Feed rate	Cost per unit ($)	Cost per year	
				3-MGD plant ($)	50-MGD plant ($)
Quicklime, CaO	pH adjustment	1–20 mg/L 8–170 lb/MG	63/ton bulk	277–5,865	4,500–97,700
Hydrated lime, $Ca(OH)_2$	pH adjustment	1–20 mg/L 8–170 lb/MG	78/ton bag 65/ton bulk	342–7,254 285–6,045	5,700–121,000 4,750–101,000
Caustic soda, NaOH (50% solution)	pH adjustment	1–20 mg/L 12–150 lb/MG	200/ton bulk	1,310–21,900	27,400–456,000
Soda ash, Na_2CO_3	pH adjustment	1–40 mg/L 8–350 lb/MG	16/cwt bag 152/ton bulk	1,402–61,320 666–30,375	23,400–>1,000,000 11,100–506,000
Inorganic phosphates	Inhibitor	3 mg/L 25 lb/MG	65/cwt bag	17,800	297,000
Sodium silicate	Inhibitor	2–8 mg/L 17–67 lb/MG	5.00/cwt tank	930–3,670	15,500–61,200

Source: Various chemical suppliers.

GLOSSARY OF CORROSION-RELATED TERMS*

Active—a state in which metal tends to corrode (opposite of passive).

Active metal—a metal ready to corrode, or being corroded.

Additive—a substance added in a small amount, usually to a fluid, for a special purpose—such as to reduce friction, corrosion, etc.

Aeration cell—an oxygen concentration cell; an electrolytic cell resulting from differences in dissolved oxygen at two points.

Aggressive—a property of water which favors the corrosion of its conveying structure.

Aggressive Index (AI)—corrosion index established by the American Water Works Association (AWWA) Standard C-400; established as a criterion for determining the corrosive tendency of the water relative to asbestos-cement pipe; calculated from the pH, calcium hardness (H), and total alkalinity (A) by the formula $AI = pH + \log(AH)$.

Alkalinity—the capacity of a water to neutralize acids; a measure of the buffer capacity of a water. The major portion of alkalinity in natural waters is caused by (1) hydroxide, (2) carbonates, (3) and bicarbonates.

Aerobic—presence of unreacted or free oxygen (0_2).

Anaerobic—an absence of unreacted or free oxygen [oxygen as H_2O Na_2SO_4 (reacted) is not "free"].

Anion—an ion or radical which is attracted to the anode because of the negative charge on the ion or radical (as Cl^-, OH^-).

Anode—(opposite of cathode) the electrode at which oxidation or corrosion occurs. A common anode reaction is:

$$Zn \rightarrow Zn^{++} + 2 \text{ electrons.}$$

Anodic polarization—polarization of anode; i.e., the decrease in the initial anode potential resulting from current flow effects at or near the anode surface. Potential becomes more noble (more positive) because of anodic polarization.

Anodic protection—an appreciable reduction in corrosion by making a metal an anode and maintaining this highly polarized condition with very little current flow.

Aqueous—pertaining to water; an aqueous solution is a water solution.

Bicarbonate alkalinity—that part of the total alkalinity that is due to the bicarbonate ion (HCO_3^-).

Bimetallic corrosion—corrosion resulting from dissimilar metal contact; galvanic corrosion.

Biological corrosion—corrosion that results from a reaction between the pipe material and organisms such as bacteria, algae, and fungi.

Carbonate alkalinity—that part of the total alkalinity due to the carbonate ion ($CO_3^{=}$).

Cathode (opposite of anode)—the electrode where reduction (and practically no corrosion) occurs. A typical cathode reaction:

$$4 \text{ electrons} + O_2 + 2H_2O \quad 4OH^-$$

Cathodic corrosion—an unusual condition (esp. with Al, Zn, Pb) in which corrosion is accelerated at the cathode because cathodic reaction creates an alkaline condition which is corrosive to certain metals.

---

* Portions of this glossary were prepared by Anton deS. Brasunas, Professor of Metallurgical Engineering, University of Missouri—Rolla for the NACE Basic Corrosion Course.

Cathodic polarization—polarization of the cathode; a reduction from the initial potential resulting from current flow effects at or near the cathode surface. Potential becomes more active (negative) because of cathodic polarization.

Cathodic protection—reduction or elimination of corrosion by making the metal a cathode by means of an impressed d.c. current or attachment to a sacrificial anode (usually Mg, Al, or Zn).

Cation—A positively charged ion (H^+, Zn^{++}) or radical (as NH_4^+) which migrates toward the cathode.

Cavitation—formation and sudden collapse of vapor bubbles in a liquid; usually resulting from local low pressures—as on the trailing edge of a propeller; this develops momentary high local pressure which can mechanically destroy a portion of a surface on which the bubbles collapse.

Cavitation-corrosion—corrosion damage resulting from cavitation and corrosion: metal corrodes, pressure develops from collapse of the cavity and removes corrosion product, exposing bare metal to repeated corrosion.

Cavitation-damage—deterioration of a surface caused by cavitation (sudden formation and collapse of cavities in a liquid).

Cavitation-erosion—see "Cavitation damage," the preferred term.

Cell—a circuit consisting of an anode and a cathode in electrical contact in a solid or liquid electrolyte. Corrosion generally occurs only at anodic areas.

Concentration cell—a cell involving an electrolyte and two identical electrodes, with the potential resulting from differences in the chemistry of the environments adjacent to the two electrodes.

Concentration polarization—polarization of an electrode caused by concentration changes in the environment adjacent to the metal surface.

Conductivity—a measure of the ability of a solution to carry an electrical current. Conductivity varies both with the number and type of ions the solution carries.

Corrosion—the destruction of a substance, usually a metal, or its properties because of a reaction with its (environment) surroundings.

Corrosion-erosion—corrosion which is increased because of the abrasive action of a moving stream; the presence of suspended particles greatly accelerates abrasive action.

Corrosion fatigue—the combined action of corrosion and fatigue (cycling stress) in causing metal fracture.

Corrosion index—measurement of the corrosivity of a water (e.g., Langelier Index, Ryznar Index, Aggressive Index, etc.).

Corrosion potential—the potential that a corroding metal exhibits under specific conditions of concentration, time, temperature, aeration, velocity, etc.

Corrosion rate—the speed (usually an average) with which corrosion progresses (it may be linear for a while); often expressed as though it were linear, in units of mdd (milligrams per square decimeter per day) for weight change, or mpy (mils per year) for thickness changes.

Couple—a cell developed in an electrolyte resulting from electrical contact between two dissimilar metals.

Crevice corrosion—localized corrosion resulting from the formation of a concentration cell in a crevice formed between a metal and a nonmetal, or between two metal surfaces.

Dealloying—the selective corrosion (removal) of or a metallic constituent from an alloy—usually in the form of ions.

Demineralization—removal of dissolved mineral matter, generally from water.

Depolarization—the elimination or reduction of polarization by physical or chemical means; depolarization results in increased corrosion.

Deposit attack (deposition corrosion)—pitting corrosion resulting from deposits on a metal surface which cause concentration cells.

Dezincification—the parting of zinc from an alloy (in some brasses, zinc is lost, leaving a weak, brittle, porous, copper-rich residue behind).

Distribution lines—those facilities used to carry water from the transmission lines to the service lines, including water mains, distribution reservoirs, elevated storage tanks, booster stations, and valves.

Electrical current—an electric current is caused by the flow of electrons. However, the electric current flows in a direction opposite to the flow of electrons. (This is accepted though seemingly illogical.

Electrochemistry—the result of an electrical and chemical reaction such as when a metal goes into solution as an ion or reacts in water with another element to form a compound resulting in a flow of electrons (electricity).

Electrochemical methods—direct corrosion monitoring method based on the electrochemical nature of corrosion in water. Measures instantaneous corrosion rates, usually in mils per year (mpy).

Electrochemical reaction—a chemical reaction involving the transfer of electrons which involves oxidation (the loss of electrons) and reduction (the gain of electrons).

Electrode—a metal in contact with an electrolyte which serves as a site where an electrical current enters the metal or leaves the metal to enter the solution.

Electrolysis—chemical changes in an electrolyte caused by an electrical current. The use of this term to mean corrosion by stray currents should be discouraged.

Electrolyte—an ionic conductor (usually in aqueous solution).

Electron acceptor—any substance which accepts electrons from some other substance in an electrochemical reaction.

Equilibrium potential—the electrode potential at equilibrium.

Erosion—deterioration of a surface by the abrasive action of moving fluids. This is accelerated by the presence of solid particles or gas bubbles in suspension. When deterioration is further increased by corrosion, the term "erosion-corrosion" is often used.

Fatigue—a process leading to fracture resulting from repeated stress cycles well below the normal tensile strength. Such failures start as tiny cracks which grow to cause total failure.

Filiform corrosion—(see "Underfilm corrosion," the preferred term).

Film—a thin surface layer that may or may not be visible.

Fouling—a term used to describe the covering of submerged surfaces covered by marine growths such as barnacles.

Galvanic—pertaining to an effect caused by the cell—often dissimilar metal contact which results in electrolytic potential.

Galvanic cell—a cell consisting of two dissimilar metals in contact with each other and with a common electrolyte (sometimes refers to two similar metals in contact with each other but with dissimilar electrolytes; differences can be small and more specifically defined as a concentration cell).

Galvanic corrosion—corrosion that is increased because of the current caused by a galvanic cell (sometimes called "couple action").

Galvanic series—a list of metals arranged according to their relative corrosion potentials in some specific environment; sea water is often used.

General corrosion—corrosion in a uniform manner.

Graphitization (graphitic corrosion)—corrosion of gray cast iron in which the metallic constituents are converted to corrosion products, leaving the graphite flakes intact. Graphitization is also used in a metallurgical sense to mean the decomposition of iron carbide to form iron and graphite.

Grain—a portion of a solid metal (usually a fraction of an inch in size) in which the atoms are arranged in an orderly pattern. The irregular junction of two adjacent grains is known as a grain boundary. (Also a unit of weight, 1/7000th of a pound.)

Half cell—a pure metal in contact with a solution of known concentration of its own ion, at a specific temperature develops a potential which is characteristic and reproducible; when coupled with another half cell, an overall potential develops which is the sum of both half cells.

Inert material—a material which is not very reactive, such as a noble metal, plastic, or cement.

Inhibitor—a substance which sharply reduces corrosion, when added to water, acid, or other liquid in small amounts.

Internal corrosion—corrosion that occurs inside a pipe because of the physical, chemical, or biological interactions between the pipe and the water as opposed to forces acting outside the pipe, such as soil, weather, or stress conditions.

Ion—an electrically charged atom (Na^+, Al^{+3}, Cl^-, S^{-2}) or group of atoms known as "radicals" (NH_4^+, SO_4^{-2} PO_4^{-3}).

Ionization—dissociation of ions in an aqueous solution (e.g., $H_2\,CO^3 \rightleftharpoons H^+ + HCO_3^-$ or $H_2O \rightleftharpoons H^+ + OH^-$).

Langelier Index—a calculated saturation index for calcium carbonate that is useful in predicting scaling behavior of natural water.

Local action—corrosion due to action of local cells, i.e., galvanic cells caused by nonuniformities between two adjacent areas at a metal surface exposed to an electrolyte.

Local cell—a galvanic cell caused by small differences in composition in the metal or the electrolyte.

Metal ion concentration cell—a galvanic cell caused by a difference in metal ion concentration at two locations on the same metal surface.

National Interim Primary Drinking Water Regulations (NIPDWR)—regulations established by EPA (*Federal Register*, Vol. 40, No. 51—March 14, 1975) which set maximum contaminant levels (MCLs) for various parameters in public drinking water systems to protect the public health.

National Secondary Drinking Water Regulations (NSDWR)—regulations established by EPA (*Federal Register*, Vol. 42, No. 62—March 31, 1977) which specify secondary maximum contaminant levels (SMCLs) for 12 parameters which primarily affect the aesthetic qualities relating to the public acceptance of drinking water.

Noble metal—a metal which is not very reactive—as silver, gold, copper—and may be found naturally in metallic form on earth.

Nonuniform corrosion—corrosion that attacks small, localized areas of the pipe. Usually results in less metal loss than uniform corrosion but causes more rapid failure of the pipe due to pits and holes.

Oxidation—loss of electrons, as when a metal goes from the metallic state to the corroded state (opposite of "Reduction"). Thus, when a metal reacts with oxygen, sulfur, etc. to form a compound as oxide, sulfide, etc., it is oxidized.

Oxidizing agent—a chemical or substance that causes a loss of electrons such as causing a metal to go from the metallic state to the corroded state. An electron acceptor.

Oxygen concentration cell—a galvanic cell caused by a difference in oxygen concentration at two points on a metal surface.

Passivator—an inhibitor which changes the potential of a metal appreciably to a more cathodic or noble value (as when chromate is added to water).

Passive—the state of a metal when its behavior is much more noble (resists corrosion) than its position in the Emf series would predict. This is a surface phenomenon.

Passive-active cell—a cell composed of a metal in the passive state and the same metal in the active state.

Passivity—the phenomenon of an active metal becoming passive.

pH—a measure of the acidity or alkalinity of a solution. A value of seven is neutral; low numbers are acid, large numbers are alkaline. Strictly speaking, pH is the negative logarithm of the hydrogen ion concentration.

pH_s—the pH at which a water is saturated with calcium carbonate ($CaCO_3$).

Pitting—highly localized corrosion resulting in deep penetration at only a few spots.

Pitting factor—the depth of the deepest pit divided by the "average penetration" as calculated from weight loss.

Polarization—the shift in electrode potential resulting from the effects of current flow, measured with respect to the "zero-flow" (reversible) potential; i.e., the counter-emf caused by the products formed or concentration changes in the electrolyte.

Protective potential—a term sometimes used in cathodic protection to define the minimum potential required to suppress corrosion. For steel in sea water, this is claimed to be about 0.85 volt as measured against a saturated calomel.

Raman spectroscopy—a direct corrosion monitoring method that reflects an infrared beam off a pipe surface and records the change in frequency of the beam as the Raman spectrum. The spectrum, which is different for all compounds, is compared with Raman spectra of known materials to identify constituents of the corrosion film on the pipe system.

Reduction—gain of electrons, as when copper is electro-plated on steel from a copper sulfate solution (opposite of "Oxidation").

Rusting—corrosion of iron or an iron base alloy to form a reddish-brown product which is primarily hydrated ferric oxide.

Saturated solution—a solution that can dissolve no more of a given substance and will not precipitate any of that substance.

Scaling—(1) high-temperature corrosion resulting in formation of thick corrosion product layers. (2) Deposition of insoluble materials on metal surfaces, usually inside water boilers or heat exchanger tubes.

Selective corrosion—the selective corrosion of certain alloying constituents from an alloy (as dezincification) or in an alloy (as internal oxidation)

Solubility—the amount of one substance that will dissolve in another to produce a saturated solution.

Stabilization—the production of a water that is exactly saturated with calcium carbonate ($CaCO_3$).

Stray current corrosion—corrosion that is caused by stray currents from some external source.

Supersaturated solution—a solution that contains more of one substance than needed to be saturated.

Thermogalvanic corrosion—galvanic corrosion resulting from temperature differences at two points.

Tuberculation—localized corrosion at scattered locations resulting in knoblike mounds.

Underfilm corrosion—corrosion which occurs under lacquers and other organic films in the form of randomly distributed hairlines (also called "Filiform corrosion").

Undersaturated solution—a solution that contains less of a substance than needed to saturate it.

Uniform corrosion—corrosion that results in an equal amount of material loss over an entire pipe surface.

X-Ray diffraction—a direct corrosion monitoring method that identifies the scale constituents on a pipe by evaluation of a diffraction pattern.

Weight-loss method—a direct corrosion monitoring method that measures the rate of corrosion by metallic weight loss from a pipe section (or coupon) that has been contacted with a water supply over a period of time.

Additional Source Materials for Chapter 2

Adams, O.H. 1977. "The Safe Drinking Water Act Impacts on State Water Programs," presented at the 5th Annual American Water Works Association Water Quality Technology Conference, Kansas City, Mo., December 1977.

Craun, G.F., and McCabe, L.J. 1975. "Problems Associated with Metals in Drinking Water," *Journal of the American Water Works Association*, November 1975, pp. 593-599.

Hudson, H.E., Jr., and Gilcreas, F.W. 1976. "Health and Economic Aspects of Water Hardness and Corrosiveness," *Journal of the American Water Works Association*, 68(4): 201-204.

Sussman, S. 1978. "Implications of the EPA Proposed National Secondary Drinking Water Regulation on Corrosivity," presented at the American Water Works Association Seminar on Controlling Corrosion Within Water Systems, Atlantic City, N.J., June 1978.

U.S. Environmental Protection Agency. 1975. Primary Drinking Water—Proposed Interim Standards. *Federal Register*, 40(51): 11990-11998

1977a. Drinking Water and Health Recommendations of the National Academy of Sciences. *Federal Register*, 42(132): 35764-35779.

1977b. National Secondary Drinking Water Regulations—Proposed Regulations, *Federal Register*, 42(62): 17143-17147.

1981. National Interim Primary Drinking Water Regulations, *Code of Federal Regulations*, Title 40, Part 141, pp. 309-354.

Additional Source Materials for Chapter 3

AWWA Research Foundation. 1982a. Research News: Corrosion Control, No. 32, Denver, Colo.

1982b. Water Quality Research News. Treatment: Control of Lead Concentrations, No. 30, Denver, Colo.

Buelow, R.W., Millette, J.R., McFarren, E.F., and Symons, J.M. 1979. The Behavior of Asbestos-Cement Pipe Under Various Water Quality Conditions: A Progress Report, U.S. Environmental Protection Agency, Municipal Environmental Research Laboratory, Drinking Water Research Division, Cincinnati, Ohio.

Christman, R.F., and Ghassemi, M. 1966. "Chemical Nature of Organic Color in Water." *Journal of the American Water Works Association*, 58(6): 723-741.

Craun, G.F., and McCabe, L.J. 1975. "Problems Associated with Metals in Drinking Water," *Journal of the American Water Works Association*, November 1975, pp. 593-599.

Davis, M.J., Herndon, B.L., Shea, E.P., and Snyder, M.K. 1979. Occurrence, Economic Implications, and Health Effects Associated with Aggressive Waters in Public Water Supply Systems: Final Report. Midwest Research Institute, Kansas City, Mo.

Gros, W.F.H. 1977. Internal Corrosion in Water Distribution Systems, presented at the 5th Annual American Water Works Association Water Quality Technology Conference, Kansas City, Mo., December 1977.

Houck, D.H. 1981. Structural Performance of Asbestos-Cement Pipe in Corrosive Potable Water Environment, Paper No. 73, presented at the International Corrosion Forum, Toronto Ontario, Canada, April 6-10, 1981.

Karalekas, P.C., Jr. 1980. Water Treatment for Control of Lead Corrosion, presented at the New England Water Works Association Seminar on Corrosion Control in Drinking Water Systems, Randolf, Mass., March 24-25, 1980.

Kruger, J. 1981. Corrosion: Its Character and Consequences. ASTM Standardization News, 9(5): 21-23.

Larson T.E. 1975. Corrosion by Domestic Waters. Prepared for the State of Illinois, State Water Survey Division, Urbana, Ill.

Lassovszky, P., Vogt, C., and Cotruvo, J.A. 1980. Environmental Protection Agency Activities Concerning Corrosion in Municipal Drinking Water Systems, presented at the New England Water Works Association Seminar on Corrosion Control in Drinking Water Systems, Randolf, Mass., March 24-25, 1980.

McFarren, E.F., Buelow, R.W., Thurnou, R.C., Gardels, M., Sorrell, R.K., Snyder, P., and Dressman, R.C. 1977. Water Quality Deterioration in the Distribution System, presented at the 5th Annual American Water Works Association Water Quality Technology Conference, Kansas City, Mo., December 1977.

Rossi, D.L. 1980. Causes of Corrosion, presented at the New England Water Works Association Seminar on Corrosion Control in Drinking Water Systems, Randolf, Mass., March 24-25, 1980.

Sanders, D.O., 1978. Bacterial Growth and Effect, presented at the American Water Works Association Seminar on Controlling Corrosion Within Water Systems, Atlantic City, N.J., June 1978.

Schock, M.R., Logsdon, G.S., and Clark, P.J. 1981. Evaluation and Control of Asbestos-Cement Pipe Corrosion. U.S. Environmental Protection Agency, Municipal Environmental Research Laboratory, Drinking Water Research Division, Cincinnati, Ohio.

Singley, J.E. 1978. Principles of Corrosion, presented at the American Water Works Association Seminar on Controlling Corrosion Within Water Systems, Atlantic City, N.J., June 1978.

Stumm, W., and Morgan, J.J., 1981. Aquatic Chemistry: An Introduction Emphasizing Chemical Equilibria in Natural Waters, Wiley Interscience, New York.

Sylvester, M., and Cornelius, W.K. 1979. Factors Influencing Corrosiveness of Well Water Toward Copper Piping Systems. Prepared by the Johns Hopkins School of Hygiene and Public Health, Baltimore Md., for the U.S. Environmental Protection Agency, Municipal Environmental Research Laboratory, Cincinnati, Ohio.

Taylor, F.B. 1980. Metals—Corrosion or Dissolution, presented at the New England Water Works Association Seminar on Corrosion Control in Drinking Water Systems, Randolf, Mass., March 24-25, 1980.

U.S. Environmental Protection Agency. 1975. Primary Drinking Water—Proposed Interim Standards, *Federal Register*, 40(51): 11990-11998.

1977. Drinking Water and Health—Recommendations of the National Academy of Sciences, *Federal Register*, 42(132): 35764-35779.

Victoreen, H.I. 1978. Microbial Intervention in Corrosion and Discolored Water, presented at the American Water Works Association Seminar on Controlling Corrosion Within Water Systems, Atlantic City, N.J., June 1978.

Von Wolzogen Kuhr, C.A.H., and Van der Vlugt, L.S., 1953. "Aerobic and Anaerobic Iron Corrosion in Water Mains," *Journal of the American Water Works Association*, 45(1): 33-46.

Additional Source Materials for Chapter 4

Anonymous. 1981. 1981 Water Main Pipe Survey: Cost, Not Material, Shifting Pipe Choice, *American City and County*, June 1981, pp. 41-44.

AWWA Staff Report. 1960. A Survey of Operating Data for Water Works in 1960—Staff Report, American Water Works Association, Inc., New York.

AWWA Standards Committee on Plastic Pipe. 1971. "Plastic Pipe and the Water Utility—Committee Report," *Journal of the American Water Works Association*, 63(6): 352-354.

AWWA Task Group. 1960. "Cold-Water Corrosion of Copper Tubing," *Journal of the American Water Works Association*, 52(8): 1033-1040.

Bottles, D.G. 1970. "Use of Plastic Pipe," *Journal of the American Water Works Association*, 62(1): 55-58.

Buelow, R.W., Millette, J.R., McFarren, E.F., and Symons, J.M. 1979. The Behavior of Asbestos-Cement Pipe Under Various Water Quality Conditions: A Progress Report, U.S. Environmental Protection Agency, Municipal Environmental Research Laboratory, Drinking Water Research Division, Cincinnati, Ohio.

Davis, M.J., Herndon, B.L., Shea, E.P., and Snyder, M.K. 1979. Occurrence, Economic Implications, and Health Effects Associated with Aggressive Waters in Public Water Supply Systems: Final Report. Midwest Research Institute, Kansas City, Mo.

Dressendorfer, P.V., and Halff, A.H. 1972. Large Water Mains: Experience and Practice of Three Large Users, *Journal of the American Water Works Association*, 64(7): 435-440.

Fitzgerald, J.H., III. 1968. Corrosion as a Primary Cause of Cast-Iron Main Breaks, *Journal of the American Water Works Association*, 60(8): 882-897.

Gros, W.F.H. 1977. Internal Corrosion in Water Distribution Systems, presented at the 5th Annual American Water Works Association Water Quality Technology Conference, Kansas City, Mo., December 1977.

Higgins, M.J. 1980. Ductile Iron Pipe Corrosion, presented at the New England Water Works Association Seminar on Corrosion Control in Drinking Water Systems, Randolf, Mass., March 24-25, 1980.

Houck, D.H. 1981. Structural Performance of Asbestos-Cement Pipe in Corrosive Potable Water Environment, Paper No. 73, presented at the International Corrosion Forum, Toronto, Ontario, Canada, April 6-10, 1981.

Hucks, R.T., Jr. 1972. Designing PVC Pipe for Water-Distribution Systems, *Journal of the American Water Works Association*, 64(7): 443-447.

Hudson, W.D. 1966. Studies in Distribution System Capacity in Seven Cities, *Journal of the American Water Works Association*, 58(2): 157-164.

Karalekas, P.C., Jr. 1980. Water Treatment for Control of Lead Corrosion, presented at the New England Water Works Association Seminar on Corrosion Control in Drinking Water Systems, Randolf, Mass., March 24-25, 1980.

Larson T.E. 1975. Corrosion by Domestic Waters. Prepared for the State of Illinois, State Water Survey Division, Urbana, Ill.

Lassovszky, P., Vogt, C., and Cotruvo, J.A. 1980. Environmental Protection Agency Activities Concerning Corrosion in Municipal Drinking Water Systems, presented at the New England Water Works Association Seminar on Corrosion Control in Drinking Water Systems, Randolf, Mass., March 24-25, 1980.

Leckie, H.P., and Uhlig, H.H. 1966. Environmental Factors Affecting the Critical Potential for Pitting in 18-8 Stainless Steel, *Journal of the Electrochemical Society*, 113(12): 1262-1267.

McCabe, L.J., Symons, J.M., Lee, R.D., and Robeck, G.G. 1970. Survey of Community Water Supply Systems, *Journal of the American Water Works Association*, 62(11): 670-687.

McFarren, E.F., Buelow, R.W., Thurnou, R.C., Gardels, M., Sorrell, R.K., Snyder, P., and Dressman, R.C. 1977. Water Quality Deterioration in the Distribution System, presented at the 5th Annual American Water Works Association Water Quality Technology Conference, Kansas City, Mo., December 1977.

Miller, W.T. 1965. Durability of Cement—Mortar Linings in Cast-Iron Pipe. *Journal of the American Water Works Association*, 57(6): 773-782.

National Association of Corrosion Engineers (NACE). 1980. Prevention and Control of Water-Caused Problems in Building Potable Water Systems, TPC Publication No. 7, Houston, Tex.

Nesbitt, W.D. 1980. PVC Water Pipe in Corrosive Environments, presented at the New England Water Works Association Seminar on Corrosion Control in Drinking Water Systems, Randolf, Mass., March 24-25, 1980.

Patterson, J.W., and O'Brien, J.E. 1979. Control of Lead Corrosion. *Journal of the American Water Works Association*, May 1979, pp. 264-271.

Scott, J.B., and Caesar, A.E. 1975. Survey of Water Main Pipe in U.S. Utilities Over 2,500 Population, prepared by *The American City Magazine*, Morgan-Grampian Publishing Co., Pittsfield, Mass.

Seidel, H.F., and Cleasby, J.L. 1966. A Statistical Analysis of Water Works Data for 1960, *Journal of the American Water Works Association*, 58(12):1507-1527.

Streicher, L. 1956. Effects of Water Quality on Various Metals, *Journal of the American Water Works Association*, 48(3): 219-238.

SumX Corporation. 1982. Final Report—Corrosion in Potable Water Systems. Prepared for the U.S. Environmental Protection Agency, Science and Technology Branch, Washington, D.C., Austin, Texas.

Taylor, F.B. 1980. Metals—Corrosion or Dissolution, presented at the New England Water Works Association Seminar on Corrosion Control in Drinking Water Systems, Randolf, Mass., March 24-25, 1980.

Timblin, L.O., Jr., Selander, C.E., and Causey, F.E. 1972. Progress Report on the Evaluation of RPM Pipe, *Journal of the American Water Works Association*, 64(7): 449-456.

Additional Source Materials for Chapter 5

Bennett, W.F., Holler, A.C., and Hurst, W.D. 1977. An Unusual Form of Corrosion, *Journal of the American Water Works Association*, 69(1):26-30.

Davis, M.J., Herndon, B.L., Shea, E.P., and Snyder, M.K. 1979. Occurrence, Economic Implications, and Health Effects Associated with Aggressive Waters in Public Water Supply Systems: Final Report. Midwest Research Institute, Kansas City, Mo.

Larson T.E. 1966. Deterioration of Water Quality in Distribution Systems, *Journal of the American Water Works Association*, 58(10): 1307-1316.

1975. Corrosion by Domestic Waters. Prepared for the State of Illinois, State Water Survey Division, Urbana, Ill.

Lassovszky, P., Vogt, C., and Cotruvo, J.A. 1980. Environmental Protection Agency Activities Concerning Corrosion in Municipal Drinking Water Systems, presented at the New England Water Works Association Seminar on Corrosion Control in Drinking Water Systems, Randolf, Mass., March 24-25, 1980.

Millette, J.R., Hammonds, A.F., Pansing, M.F., Hansen, E.C., and Clark, P.J. 1980. Aggressive Water: Assessing the Extent of the Problem, *Journal of the American Water Works Association*, 72(5): 262-266.

Morris, R.E., Jr. 1967. Principal Causes and Remedies of Water Main Breaks, *Journal of the American Water Works Association*, 59(7): 782-798.

National Association of Corrosion Engineers (NACE). 1980. Prevention and Control of Water-Caused Problems in Building Potable Water Systems, TPC Publication No. 7, Houston, Tex.

Rambow, C.A., and Holmgren, R.S., Jr. 1966. Technical and Legal Aspects of Copper Tube Corrosion, *Journal of the American Water Works Association*, 58(3): 347-353.

Singley, J.E. 1978. Principles of Corrosion, presented at the American Water Works Association Seminar on Controlling Corrosion Within Water Systems, Atlantic City, N.J., June 1978.

Additional Source Materials for Chapter 6

Adams, O.H. 1977. The Safe Drinking Water Act Impacts on State Water Programs, presented at the 5th Annual American Water Works Association Water Quality Technology Conference, Kansas City, Mo., December 1977.

American Water Works Association Water Quality Committee, Pacific Northwest Section. 1980. *Manual for Determining Internal Corrosion Potential in Water Supply Systems*, Final Draft.

American Water Works Association Committee on Corrosion and Deposition. 1978. Current Corrosion Experiences in Large Utilities: Results of a Committee Survey, presented at the American Water Works Association Annual Conference and Exposition, Atlantic City, N.J., June 1978.

American Water Works Association Research Foundation. 1982. Research News: Corrosion Control, No. 32, Denver, Colo.

American Water Works Association Research Foundation. Water Quality Research News. 1982. Treatment: Control of Lead Concentrations, No. 30., Denver, Colo.

Benedict, R.L., Opincar, V.E. 1980. Planning to Mitigate External Corrosion—Case Study, presented at the New England Water Works Association Seminar on Corrosion Control in Drinking Water Systems, Randolf, Mass., March 24-25, 1980.

Buelow, R.W., Millette, J.R., McFarren, E.F., and Symons, J.M. 1979. The Behavior of Asbestos-Cement Pipe Under Various Water Quality Conditions: A Progress Report, U.S. Environmental Protection Agency, Municipal Environmental Research Laboratory, Drinking Water Research Division, Cincinnati, Ohio.

Byars, H.G., and Gallop, B.R. 1975. An Approach to the Reporting and Evaluation of Corrosion Coupon Exposure Results, *Materials Performance*, 14(11): 9.

Casey, J.R., and Eakins, W. 1980. Impact of Cleaning and Lining Cast-Iron Pipe Corrosion— Case History of Lynn, MA, presented at the New England Water Works Association Seminar on Corrosion Control in Drinking Water Systems, Randolf, Mass., March 24-25, 1980.

Costello, J.J. 1978. Lime Use for Corrosion Control, presented at the American Water Works Association Seminar on Controlling Corrosion Within Water Systems, Atlantic City, N.J., June 1978.

Davis, M.J., Herndon, B.L., Shea, E.P., and Snyder, M.K. 1979. Occurrence, Economic Implications, and Health Effects Associated with Aggressive Waters in Public Water Supply Systems: Final Report. Midwest Research Institute, Kansas City, Mo.

Dye, J.F. 1958. Correlation of the Two Principal Methods of Calculating the Three Kinds of Alkalinity, *Journal of the American Water Works Association*, 50(6): 800-820.

Graves, D.J., and Jorden, E.C. 1980. The Use of Indices to Describe and Control Corrosion, presented at the New England Water Works Association Seminar on Corrosion Control in Drinking Water Systems, Randolf, Mass., March 24-25, 1980.

Gros, W.F.H. 1977. Internal Corrosion in Water Distribution Systems, presented at the 5th Annual American Water Works Association Water Quality Technology Conference, Kansas City, Mo., December 1977.

Grubb, C.E. 1979. Field Test of Corrosion Control to Protect Asbestos-Cement Pipe. Prepared for the U.S. Environmental Protection Agency, Municipal Environmental Research Laboratory, Drinking Water Research Division, Cincinnati. Greenwood, S.C.

Houck, D.H. 1981. Structural Performance of Asbestos-Cement Pipe in Corrosive Potable Water Environment, Paper No. 73, presented at the International Corrosion Forum, Toronto, Ontario, Canada, April 6-10, 1981.

Larson T.E. 1975. Corrosion by Domestic Waters. Prepared for the State of Illinois, State Water Survey Division, Urbana, Ill.

Lassovszky, P., Vogt, C., and Cotruvo, J.A. 1980. Environmental Protection Agency Activities Concerning Corrosion in Municipal Drinking Water Systems, presented at the New England Water Works Association Seminar on Corrosion Control in Drinking Water Systems, Randolf, Mass., March 24-25, 1980.

Logsdon, G.S., and Millette, J.R. (n.d.) Monitoring for Corrosion of A/C Pipe, U.S. Environmental Protection Agency, Drinking Water Research Division, Cincinnati, Ohio.

McCauley, R.F. 1960. Controlled Deposition of Protective Calcite Coatings in Water Mains, *Journal of the American Water Works Association*, 52(11):1386-1396.

McClanahan, M.A., and Mancy, K.H. 1974a. Comparison of Corrosion—Rate Measurements on Fresh vs. Previously Polarized Samples, *Journal of the American Water Works Association*, 66(8): 461-466.

1974b. Effect of pH on Quality of Calcium Carbonate Film Deposited from Moderately Hard and Hard Water, *Journal of the American Water Works Association*, 66(1): 49-53.

McClelland, N.I., and Mancy, K.H. 1972. Water Quality Monitoring in Distribution Systems: A Progress Report, *Journal of the American Water Works Association*, 64(12): 795-803.

McFarren, E.F., Buelow, R.W., Thornau, R.C., Gardels, M., Sorrell, R.K., Snyder, P., and Dressman, R.C. 1977. Water Quality Deterioration in the Distribution System, presented at the 5th Annual American Water Works Association Water Quality Technology Conference, Kansas City, Mo., December 1977.

McFarren, E.F., Thornau, R.W., Gardels, M., Sorrell, R.K., Snyder, P., and Dressman, R.C. 1977. Water Quality Deterioration in the Distribution System. U.S. Environmental Protection Agency, Municipal Environmental Research Laboratory, Water Supply Research Division, Cincinnati, Ohio.

Medlar, S. 1980. Evaluating Steam Corrosion, presented at the New England Water Works Association Seminar on Corrosion Control in Drinking Water Systems, Randolf, Mass., March 24-25, 1980.

Malco Chemical Co. (n.d.) Evaluating Corrosion in Steam and Water Systems, Oak Brook, Ill. Water Treatment Chemicals TF 37.

National Association of Corrosion Engineers (NACE). 1980. Prevention and Control of Water-Caused Problems in Building Potable Water Systems, TPC Publication No. 7, Houston, Tex.

Patterson, J.W., and O'Brien, J.E. 1979. Control of Lead Corrosion. *Journal of the American Water Works Association*, 71(5): 264-271.

Petrolite Corporation, Petreco Division (n.d.) *Technical Manual*: M-3010 *Corrosion Rate Instrument*, Houston, Tex.

Pourbaix, M. 1969. Recent Applications of Electrode Potential Measurements in the Thermodynamics and Kinetics of Corrosion of Metal. *Corrosion*, National Association of Corrosion Engineers, 25(6): 267.

1972. Theoretical and Experimental Considerations in Corrosion Testing. *Corrosion Science*, Vol. 12, pp. 161-191.

Ritter, J.A. 1977. Establishing a Corrosion Monitoring Program, presented at the 5th Annual American Water Works Association Water Quality Technology Conference, Kansas City, Mo., December 1977.

Schock, M.R., Logsdon, G.S., and Clark, P.J. 1981. Evaluation and Control of Asbestos-Cement Pipe Corrosion. U.S. Environmental Protection Agency, Municipal Enviromental Research Laboratory, Drinking Water Research Division, Cincinnati, Ohio.

Schock, M.R., Mueller, W., and Buelow, R.W. 1979. Laboratory Technique for Measurement of pH for Corrosion Control Studies and Waters not in Equilibrium with the Atmosphere. (Draft). U.S. Environmental Protection Agency, Physical and Chemical Contaminant Removal Branch, Cincinnati, Ohio.

Shull, K.E. 1980. An Experimental Approach to Corrosion Control, *Journal of the American Water Works Association*, May 1980, pp. 280-285.

Singley, J.E. 1981. The Search for a Corrosion Index. *Journal of the American Water Works Association*, 73(11): 579.

Singley, J.E., and Lee, T.H. 1982. Development and Use of an Apparatus for Study of Corrosion of Pipe Sections, Gainesville, Fla.

Sussman, S. 1978. "Implications of the EPA Proposed National Secondary Drinking Water Regulation on Corrosivity," presented at the American Water Works Association Seminar on Controlling Corrosion Within Water Systems, Atlantic City, N.J., June 1978.

System Water Quality Committee, California-Nevada Section, American Water Works Association. 1978. *Procedure Manual for Handling Water Quality Complaints.*

Thibeau, R.J., Brown, C.W., Goldfarb, A.Z., and Heidersbach, R.H. 1980. Raman and Infrared Spectroscopy of Aqueous Corrosion Films on Lead in 0.1 M Sulfate Solutions, *Journal of the Electrochemical Society*, 127(9): 1913-1918.

Trussell, R.R., and Russell, L.L. 1977. The Langelier Index, presented at the 5th Annual American Water Works Association Water Quality Technology Conference, Kansas City, Mo., December 1977.

University of Rhode Island, Department of Chemistry. 1980. Quarterly Report, First Quarter, In Situ Analysis of Corrosive and Passive Surfaces by Laser-Excited Raman Spectroscopy, Kingston, R.I.

U.S. Environmental Protection Agency. 1975. Primary Drinking Water—Proposed Interim Standards. *Federal Register*, 40(51): 11990-11998

1977. National Secondary Drinking Water Regulations—Proposed Regulations, *Federal Register*, 42(62): 17143-17147.

1981. National Interim Primary Drinking Water Regulations, *Code of Federal Regulations*, Title 40, Part 141, pp. 309-354.

U.S. Environmental Protection Agency, Office of Drinking Water. 1979. National Secondary Drinking Water Regulations, EPA-570/9-76-000, Washington, D.C.

U.S. Environmental Protection Agency, Office of Drinking Water, Criteria and Standards Division. 1980. Statement of Basis and Purpose for Amendments to the National Interim Primary Drinking Water Regulations, Washington, D.C.

Voyles, C.F. 1978. Stabilizing Southern California Waters, presented at the American Water Works Seminar on Controlling Corrosion Within Water Systems, Atlantic City, N.J., June 1978.

Young, W.T. 1978. Instrumentation for Evaluating Corrosion, presented at the American Water Works Association Seminar on Controlling Corrosion Within Water Systems, Atlantic City, N.J., June 1978.

Additional Source Materials for Chapter 7

American Water Works Association Research Foundation. 1982. Research News: Corrosion Control, No. 32, Denver, Colo.

American Water Works Association Research Foundation. Water Quality Research News. 1982. Treatment: Control of Lead Concentrations, No. 30, Denver, Colo.

American Water Works Association Task Group 2690-P. 1960. Cold-Water Corrosion of Copper Tubing, *Journal of the American Water Works Association*, 52(8): 1033-1040.

Bailey, T.L. 1980. Corrosion Control Experiences at Durham, North Carolina, presented at the New England Water Works Association Seminar on Corrosion Control in Drinking Water Systems, Randolf, Mass., March 24-25, 1980.

Benedict, R.L., Opincar, V.E. 1980. Planning to Mitigate External Corrosion—Case Study, presented at the New England Water Works Association Seminar on Corrosion Control in Drinking Water Systems, Randolf, Mass., March 24-25, 1980.

Buelow, R.W., Millette, J.R., McFarren, E.F., and Symons, J.M. 1979. The Behavior of Asbestos-Cement Pipe Under Various Water Quality Conditions: A Progress Report, U.S. Environmental Protection Agency, Municipal Environmental Research Laboratory, Drinking Water Research Division, Cincinnati, Ohio.

Casey, J.R., and Eakins, W. 1980. Impact of Cleaning and Lining Cast-Iron Pipe Corrosion— Case History of Lynn, MA, presented at the New England Water Works Association Seminar on Corrosion Control in Drinking Water Systems, Randolf, Mass., March 24-25, 1980.

Christman, R.F., and Ghassemi, M. 1966. Chemical Nature of Organic Color in Water, *Journal of the American Water Works Association*, 58(6): 723-741.

Costello, J.J. 1978. Lime Use for Corrosion Control, presented at the American Water Works Association Seminar on Controlling Corrosion Within Water Systems, Atlantic City, N.J., June 1978.

Davis, M.J., Herndon, B.L., Shea, E.P., and Snyder, M.K. 1979. Occurrence, Economic Implications, and Health Effects Associated with Aggressive Waters in Public Water Supply Systems: Final Report. Midwest Research Institute, Kansas City, Mo.

Ghosh, M.M. 1973. Chemical Conditioning to Control Water-Quality Failure in Distribution Systems, *Journal of the American Water Works Association*, 65(5): 348-355.

Grady, R.P. 1980. Corrosion Control Experience in Portland, Maine, presented at the New England Water Works Association Seminar on Corrosion Control in Drinking Water Systems, Randolf, Mass., March 24-25, 1980.

Gros, W.F.H. 1977. Internal Corrosion in Water Distribution Systems, presented at the 5th Annual American Water Works Association Water Quality Technology Conference, Kansas City, Mo., December 1977.

Haskew, G.M. 1978. Use of Zinc Orthophosphate Corrosion Inhibitor— Plant Practice, presented at the American Water Works Association Seminar on Controlling Corrosion Within Water Systems, Atlantic City, N.J., June 1978.

Houck, D.H. 1981. Structural Performance of Asbestos-Cement Pipe in Corrosive Potable Water Environment. Paper No. 73. Presented at the International Corrosion Forum, Toronto, Ontario, Canada, April 6-10, 1981.

Hullinger, D.L. 1975. A Study of Heavy Metals in Illinois Impoundments, *Journal of the American Water Works Association*, 67(10): 572-576.

Karalekas, P.C., Jr. 1980. Water Treatment for Control of Lead Corrosion, presented at the New England Water Works Association Seminar on Corrosion Control in Drinking Water Systems, Randolf, Mass., March 24-25, 1980.

Lane, R.W., Larson, T.E., and Schilsky, S.W. 1977. The Effect of pH on the Silicate Treatment of Hot Water in Galvanized Piping, *Journal of the American Water Works Association*, 69(8): 457-461.

Larson T.E. 1975. Corrosion by Domestic Waters. Prepared for the State of Illinois, State Water Survey Division, Urbana, Ill.

Lassovszky, P., Vogt, C., and Cotruvo, J.A. 1980. Environmental Protection Agency Activities Concerning Corrosion in Municipal Drinking Water Systems, presented at the New England Water Works Association Seminar on Corrosion Control in Drinking Water Systems, Randolf, Mass., March 24-25, 1980.

McCauley, R.F. 1960. Controlled Deposition of Protective Calcite Coatings in Water Mains, *Journal of the American Water Works Association*, 52(11):1386-1396.

McFarren, E.F., Buelow, R.W., Thornau, R.C., Gardels, M., Sorrell, R.K., Snyder, P., and Dressman, R.C. 1977. Water Quality Deterioration in the Distribution System, presented at the 5th Annual American Water Works Association Water Quality Technology Conference, Kansas City, Mo., December 1977.

Medlar, S. 1980. Evaluating Steam Corrosion, presented at the New England Water Works Association Seminar on Corrosion Control in Drinking Water Systems, Randolf, Mass., March 24-25, 1980.

Merrill, D.T., and Sanks, R.L. 1977. Corrosion Control by Deposition of $CaCO_3$ Films: Part 1, A Practical Approach for Plant Operators, *Journal of the American Water Works Association*, 69(11): 592-599.

National Association of Corrosion Engineers (NACE). 1980. Prevention and Control of Water-Caused Problems in Building Potable Water Systems, TPC Publication No. 7, Houston, Tex.

Paris, D.B. 1980. Corrosion Control in Manchester, New Hampshire, presented at the New England Water Works Association Seminar on Corrosion Control in Drinking Water Systems, Randolf, Mass., March 24-25, 1980.

Paterson, J.A. 1978. Corrosion Inhibitors and Coatings, presented at the American Water Works Association Seminar on Controlling Corrosion Within Water Systems, Atlantic City, N.J., June 1978.

Patterson, J.W., and O'Brien, J.E. 1979. Control of Lead Corrosion. *Journal of the American Water Works Association*, 71(5): 264-271.

Sanders, D.O. 1978. Bacterial Growth and Effect, presented at the American Water Works Association Seminar on Controlling Corrosion Within Water Systems, Atlantic City, N.J., June 1978.

Schock, M.R., Logsdon, G.S., and Clark, P.J. 1981. Evaluation and Control of Asbestos-Cement Pipe Corrosion. U.S. Environmental Protection Agency, Municipal Enviromental Research Laboratory, Drinking Water Research Division, Cincinnati, Ohio.

Shull, K.E. 1980. An Experimental Approach to Corrosion Control, *Journal of the American Water Works Association*, May 1980, pp. 280-285.

Stevens, R.L., and Dice, J.C. 1981. Chlorination—A Proven Means of Disinfecting Mains, *OpFlow*, 7(10): 1.

U.S. Environmental Protection Agency, Office of Drinking Water, Criteria and Standards Division. 1980. Statement of Basis and Purpose for Amendments to the National Interim Primary Drinking Water Regulations, Washington, D.C.

Victoreen, H.T. 1978. Microbial Intervention in Corrosion and Discolored Water, presented at the American Water Works Association Seminar on Controlling Corrosion Within Water Systems, Atlantic City, N.J., June 1978.

Voyles, C.F. 1978. Stabilizing Southern California Waters, presented at the American Water Works Seminar on Controlling Corrosion Within Water Systems, Atlantic City, N.J., June 1978.

Yapijakis, C. 1977. Controlling Corrosion in Distribution Systems, *Water and Sewage Works*, 124(4): 96.

Additional Source Materials for Chapter 8

Davis, M.J., Herndon, B.L., Shea, E.P., and Snyder, M.K. 1979. Occurrence, Economic Implications, and Health Effects Associated with Aggressive Waters in Public Water Supply Systems: Final Report. Midwest Research Institute, Kansas City, Mo.

Grubb, C.E. 1979. Field Test of Corrosion Control to Protect Asbestos-Cement Pipe. Prepared for the U.S. Environmental Protection Agency, Municipal Environmental Research Laboratory, Drinking Water Research Division, Cincinnati. Greenwood, S.C.

Karalekas, P.C., Jr., Ryan, C.R., and Taylor, F.B. 1982. Control of Lead Pipe Corrosion in the Boston Metropolitan Area, presented at the Annual Conference of the American Water Works Association, Miami Beach, Fla., May 16-20, 1982.

Logsdon, G.S. 1981. Project Summary: Field Test of Corrosion Control to Protect Asbestos-Cement Pipe, U.S. Environmental Protection Agency, EPA-600/S2-81-023, Cincinnati.

Additional Source Materials for Chapter 9

Bailey, T.L. 1980. Corrosion Control Experiences at Durham, North Carolina, presented at the New England Water Works Association Seminar on Corrosion Control in Drinking Water Systems, Randolf, Mass., March 24-25, 1980.

Benedict, R.L., Opincar, V.E. 1980. Planning to Mitigate External Corrosion—Case Study, presented at the New England Water Works Association Seminar on Corrosion Control in Drinking Water Systems, Randolf, Mass., March 24-25, 1980.

Courchene, J.E. 1978. Seattle Internal Corrosion Control Plan—Summary Report, presented at the American Water Works Association Seminar on Controlling Corrosion Within Water Systems, Atlantic City, N.J., June 1978.

Grady, R.P. 1980. Corrosion Control Experience in Portland, Maine, presented at the New England Water Works Association Seminar on Corrosion Control in Drinking Water Systems, Randolf, Mass., March 24-25, 1980.

Nelson, J.A. 1978. One Utility's Approach to Solving Copper Corrosion, presented at the American Water Works Association Seminar on Controlling Corrosion Within Water Systems, Atlantic City, N.J., June 1978.

Paris, D.B. 1980. Corrosion Control in Manchester, New Hampshire, presented at the New England Water Works Association Seminar on Corrosion Control in Drinking Water Systems, Randolf, Mass., March 24-25, 1980.

Ryder, R.A. 1980. The Costs of Internal Corrosion in Water Systems. *Journal of the American Water Works Association*, 72(5): 267-279.